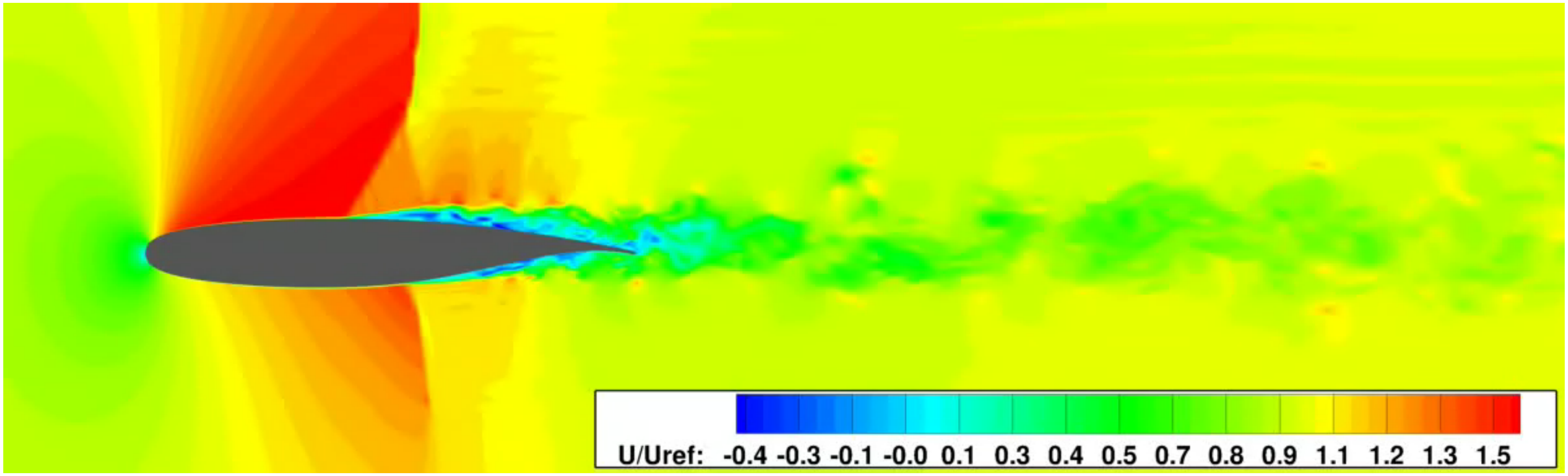
Overset Grid Simulations for the 2nd AIAA Aeroelastic Prediction Workshop



Jeffrey Housman
Computational Aerosciences Branch
NASA Ames Research Center

Advanced Modeling & Simulation Seminar Series

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AIAA-2017-0640, Housman and Kiris, 58th AIAA/ASCE/ASC Structures, Structural Dynamics, and Materials Conference, 2017

Outline

- Introduction
- Methodology
- Geometric Model
- Structured Overset Grid System
- Results from 2nd AIAA Aeroelastic Prediction Workshop
  - Case 1a: Steady-state
  - Case 1b: Forced pitch
  - Case 3a: Shock/BL separation
- Summary
- Future Work

	Case 1A	Case 1B	Case 2	Case 3A	Case 3B	Case 3C
Mach	0.7	0.7	0.74	0.85	0.85	0.85
AoA	3°	3°	0°	5°	5°	5°
Dynamic Data Type	Steady	Forced Oscillation	Flutter	Unforced Unstready	Forced Oscillation	Flutter
Notes	Attached	Attached		Separated	Separated	Separated

Introduction

- Modern aircraft are designed with flexible wings to decrease weight and increase fuel efficiency

- During cruise, the flexible wings undergo static aeroelastic deformation (Akaydin et al. AIAA-2015-2418, Denison et al. AIAA-2016-3571)

- When exposed to off-design conditions, dynamic aeroelastic coupling may occur resulting in flutter

- In an effort towards flutter prediction capability with the LAVA framework, the structured overset grid solver has been applied to a sub-set of test cases from the Second AIAA Aeroelastic Prediction Workshop

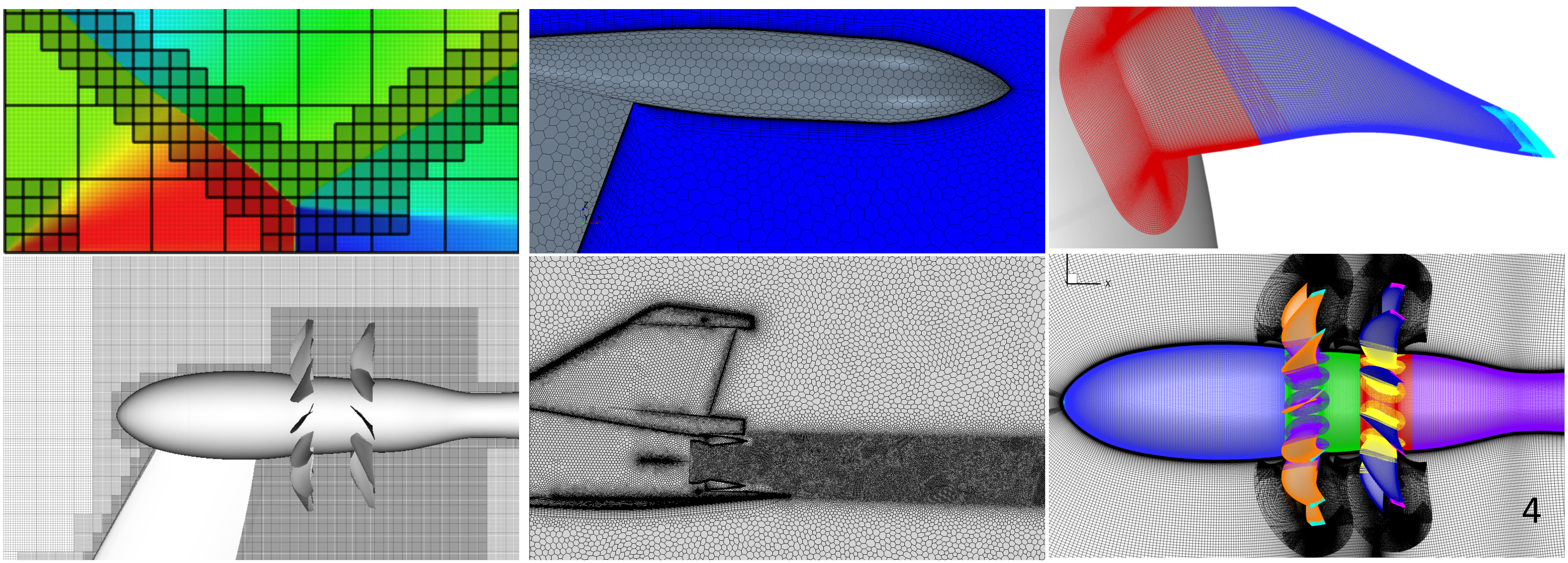
- Application of the Cartesian immersed boundary solver in LAVA has been reported in Brehm et al. AIAA-2016-3265

Computational Methodology

LAVA Framework (Kiris et al. Aerospace Science and Technology, Volume 55, 2016)

- Computational Fluid Dynamics Solvers
  - Cartesian, Curvilinear, and Unstructured Grid Types
  - Overset Grid and Immersed Boundary Capabilities
  - Steady and Unsteady RANS, LES, Hybrid RANS/LES, and LBM
- Computational Aeroelastic Solvers

Cartesian Immersed Boundary ***Unstructured Arbitrary Polyhedral*** ***Overset Structured Curvilinear***



Computational Methodology

3-D Structured Curvilinear Overset Grid Solver

- RANS, LES, and Hybrid RANS/LES
- Spalart-Allmaras (baseline turbulence model)

Higher-Order Finite Difference Method (Housman et al. AIAA-2016-2963)

- 6th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)
- Numerical flux is a modified Roe scheme
- 5th/6th-order upwind-biased/central left and right state interpolation
- 2nd-order accurate differencing used for time discretization
- Time-accurate GCL preserving high-order metric term evaluation

Modifications to DDES model

- A modified length scale reducing spanwise mesh dependence in 2D instability regions
- Near wall functions are removed when in LES mode

RANS/NLES Model

- Specified transition from RANS to Numerical LES (no SGS model)
- Turbulence model receives time-averaged flow variables

Computational Methodology

Details of Higher-Order Finite Difference Method

Explicit Form of Hybrid Weighted Compact Nonlinear Scheme (Deng et al. AIAA-2011-3857, Nonomura & Fujii Comp Fluids 2013)

$$\frac{\partial f}{\partial x} \approx a\frac{\tilde{f}_{j+1/2}(Q_{L,}Q_R) - \tilde{f}_{j-1/2}(Q_L, Q_R)}{\Delta x} + b\frac{f_{j+1} - f_{j-1}}{\Delta x} + c\frac{f_{j+2} - f_{j-2}}{\Delta x}$$

- Q_L and Q_R are evaluated with Z-WENO interpolation
- Blended Central/Upwind Option (applied to velocity only)

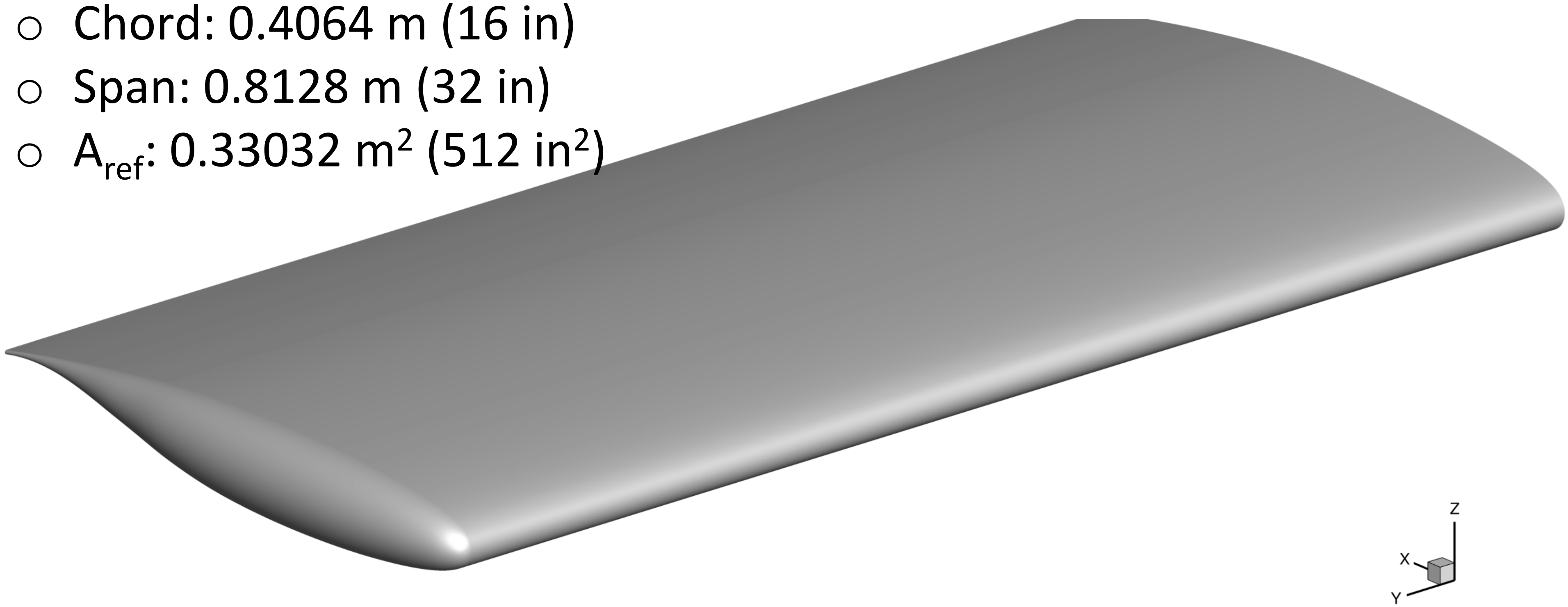
  $U_L = ½ (U_L + U_R) + ½ \text{ zeta } (U_L - U_R)$

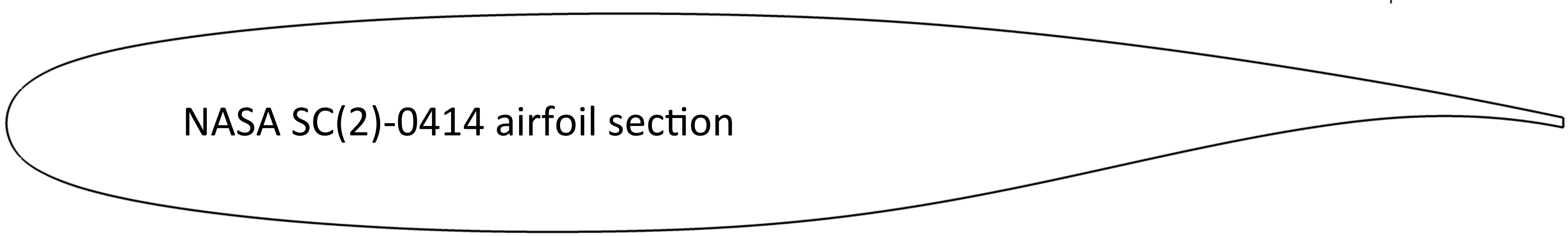
  $U_R = ½ (U_L + U_R) + ½ \text{ zeta } (U_R - U_L)$
- zeta = 1 reduces to upwind biased interpolation (5th-order)
- zeta = 0 reduces to central interpolation (6th-order)
- 0 < zeta < 1 blends the interpolation (5th-order/6th-order)
- For high-speed flows zeta depends on local flow Mach number

Geometric Model

Benchmark Super Critical Wing (BSCW)

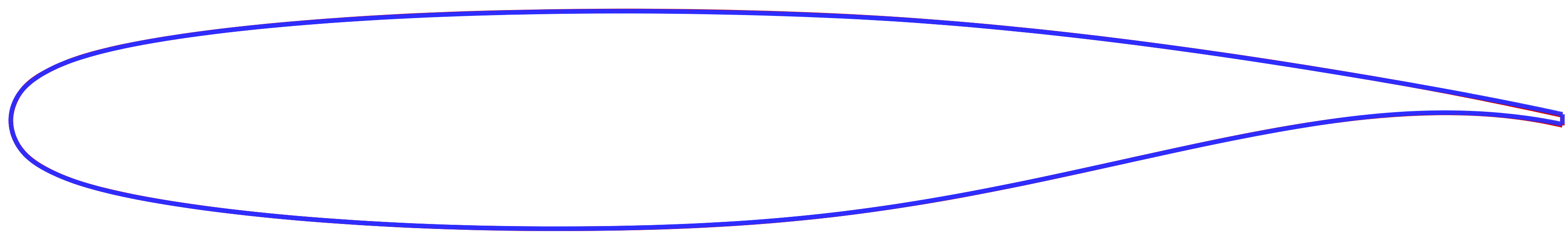
- Chord: 0.4064 m (16 in)
- Span: 0.8128 m (32 in)
- A_{ref}: 0.33032 m^2 (512 in^2)

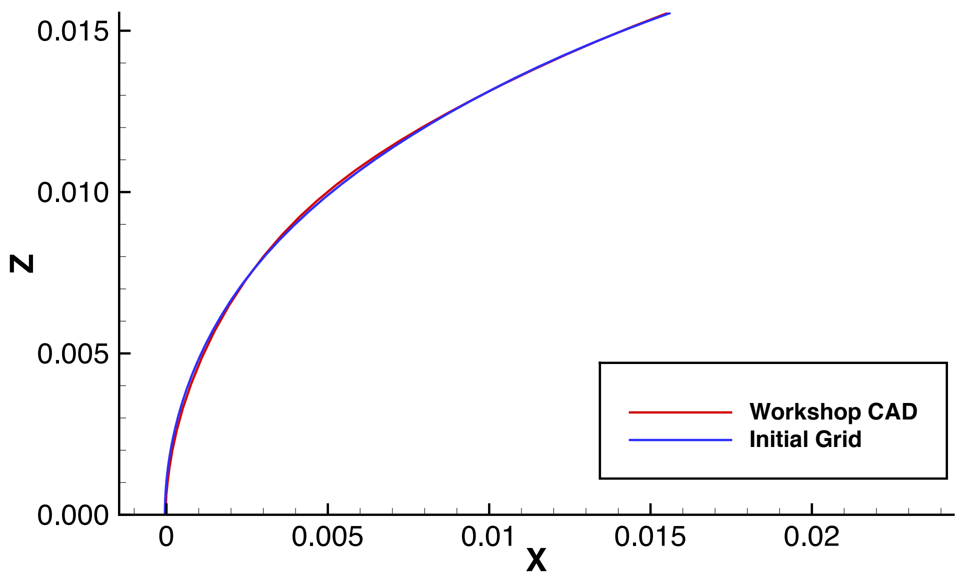


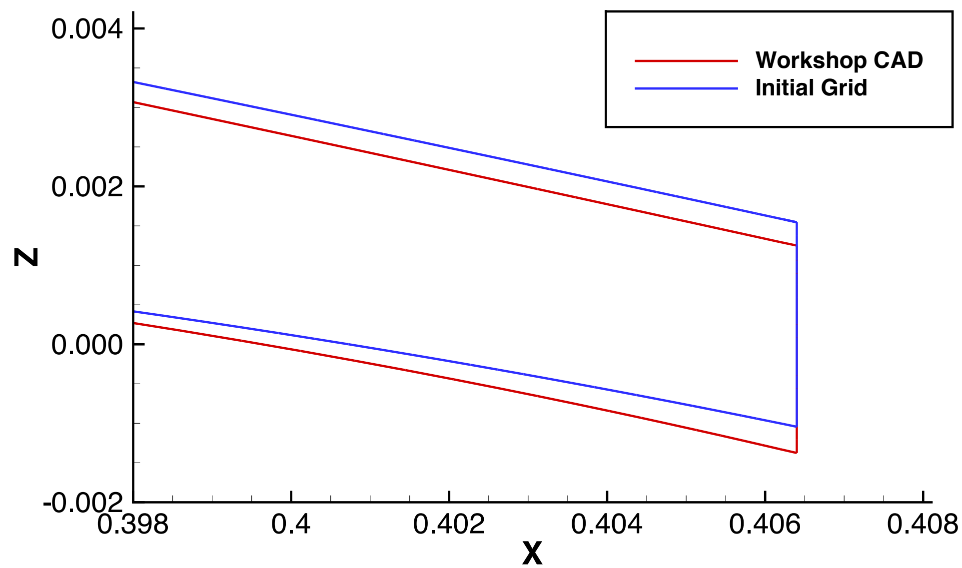


Geometric Model

Comparison of CAD and “Straight Wing” at 60 percent span

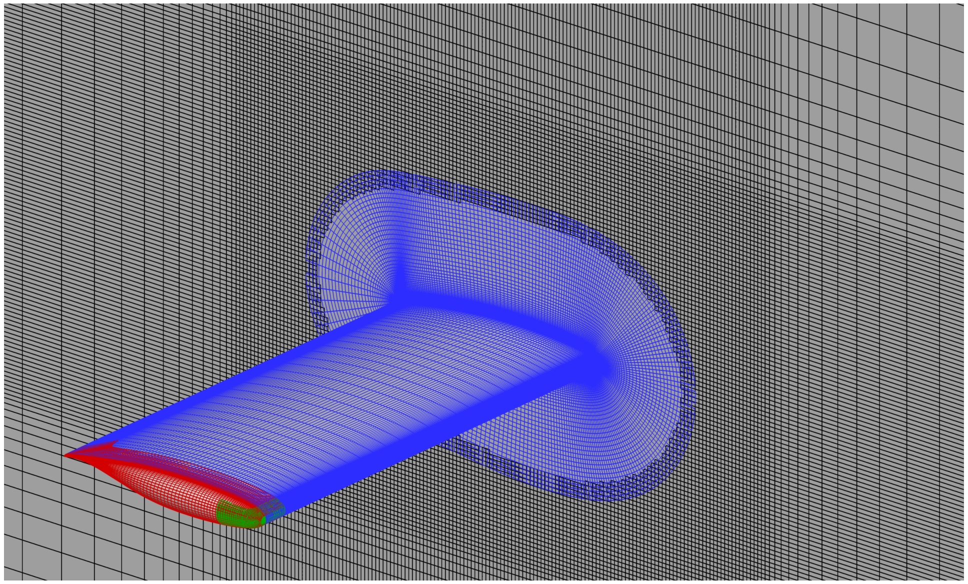




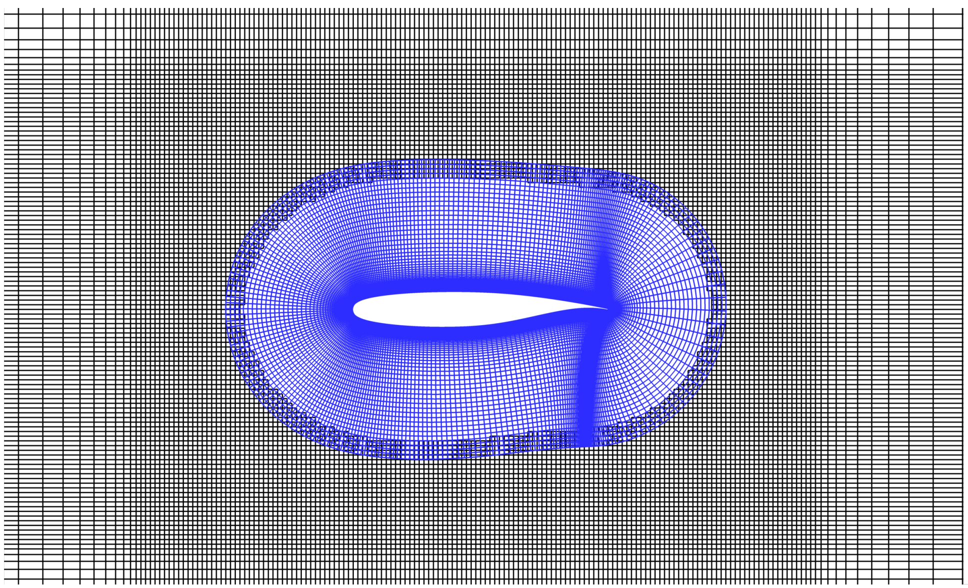


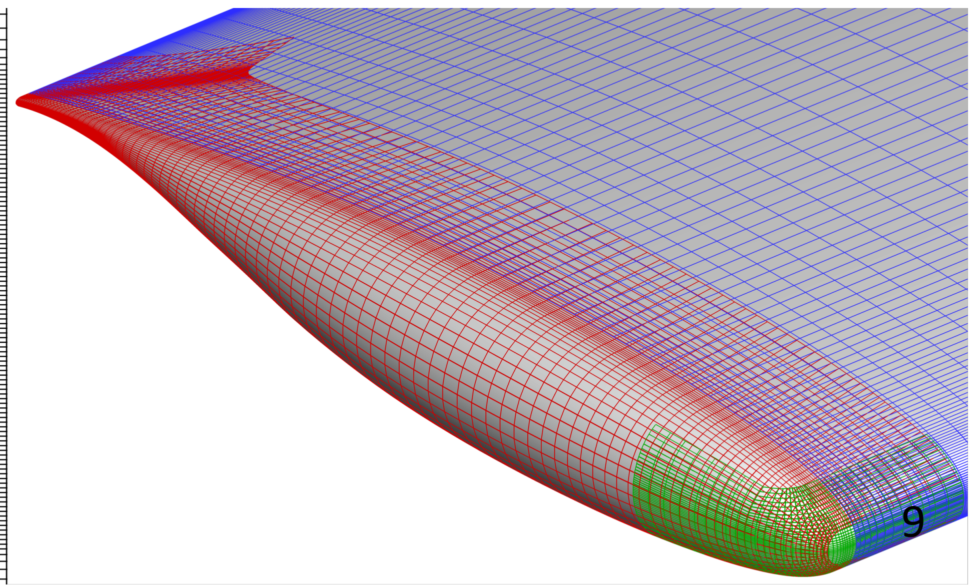
- A small discrepancy in the surface curvature along the upper surface near the leading edge
- A deflections of the trailing edge (both upward and downward) along the span

Structured Overset Grid System



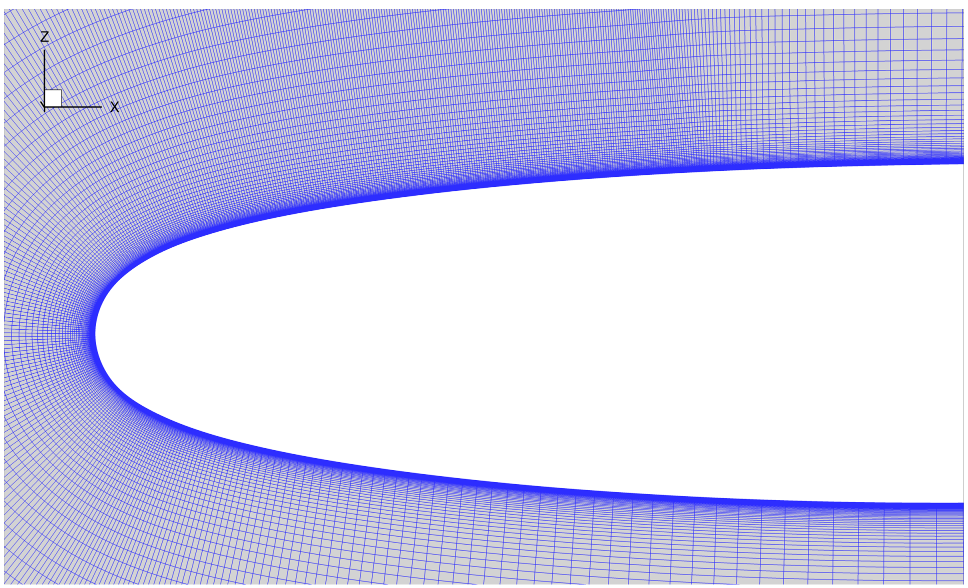
- Initially three grid systems were generated
  - Coarse: 3.9 million points
  - Medium: 7.1 million points
  - Fine: 18.1 million points
- A very-fine grid was generated for case (1b) which refined the stream-wise spacing in the shock oscillation region
  - Very-Fine: 21.7 million points

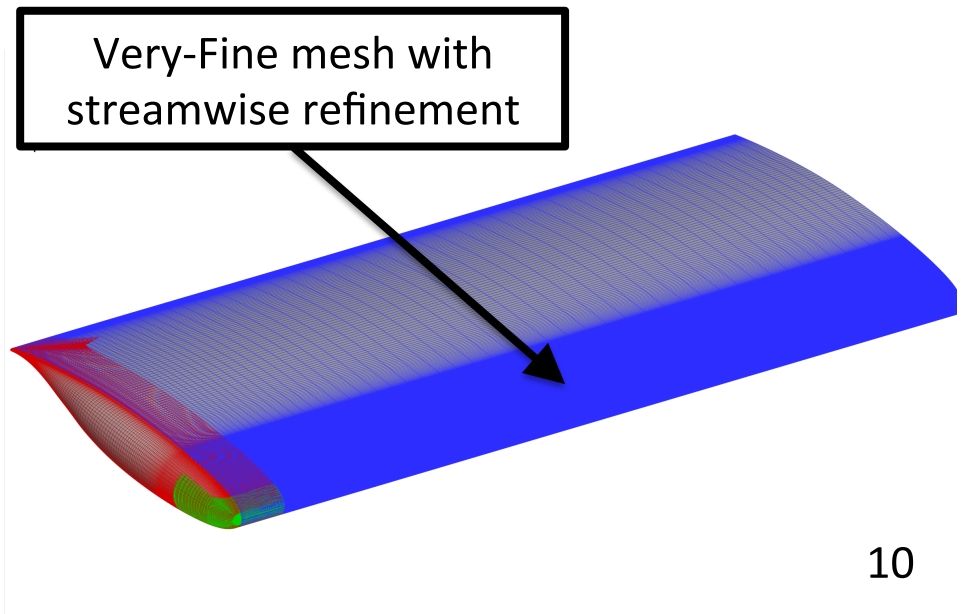




Structured Overset Grid System

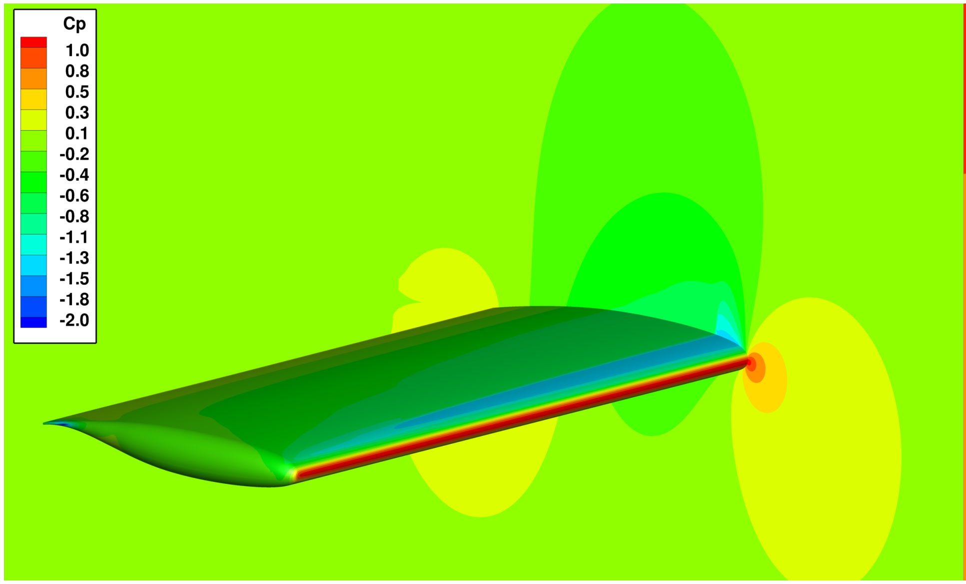
Mesh	Points ($x10^6$)	Wall (mm)	Y^+_{max}	LE (mm)	TE (mm)	Stream (mm)	Span (mm)	Tip (mm)
Coarse	3.9	0.0024	1.2	0.6	0.65	10	50	1.3
Medium	7.1	0.0016	0.8	0.4	0.325	7.5	35	0.813
Fine	18.1	0.00105	0.525	0.27	0.1625	5	22	0.535
Very-Fine	21.7	0.00105	0.525	0.27	0.1625	5	22	0.535

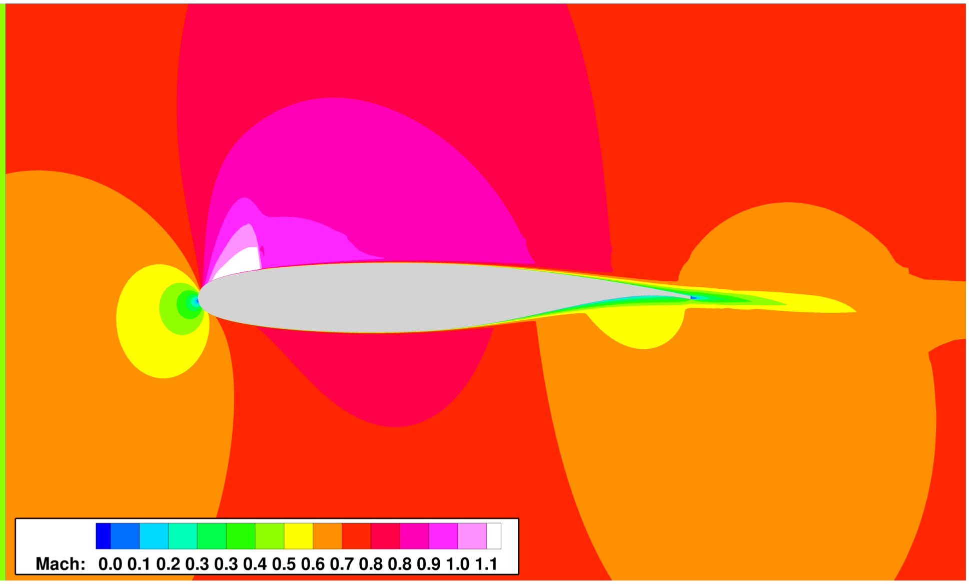


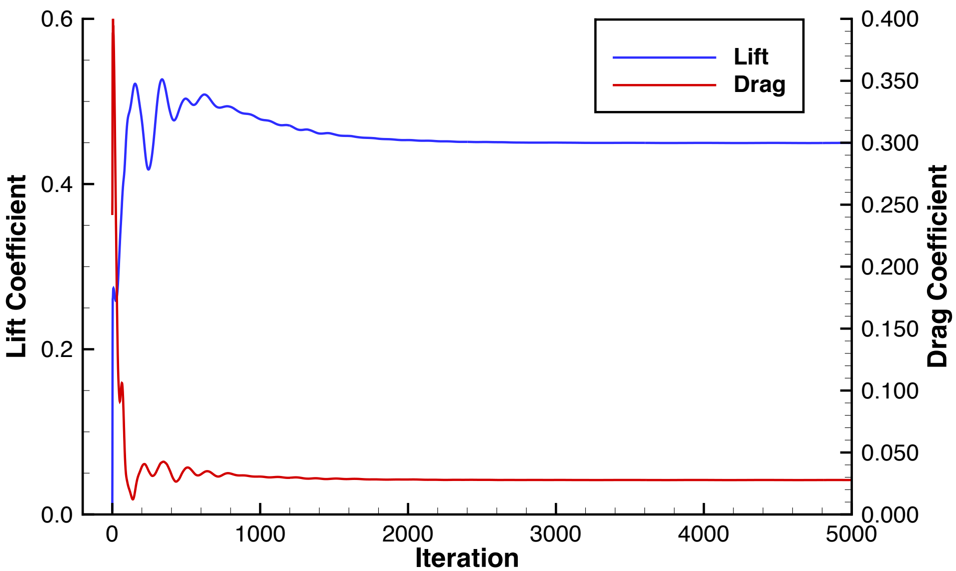


Case 1a: Steady-State

Mach: 0.7 Reynolds Number: 4.56 million (chord) AOA: 3 degrees



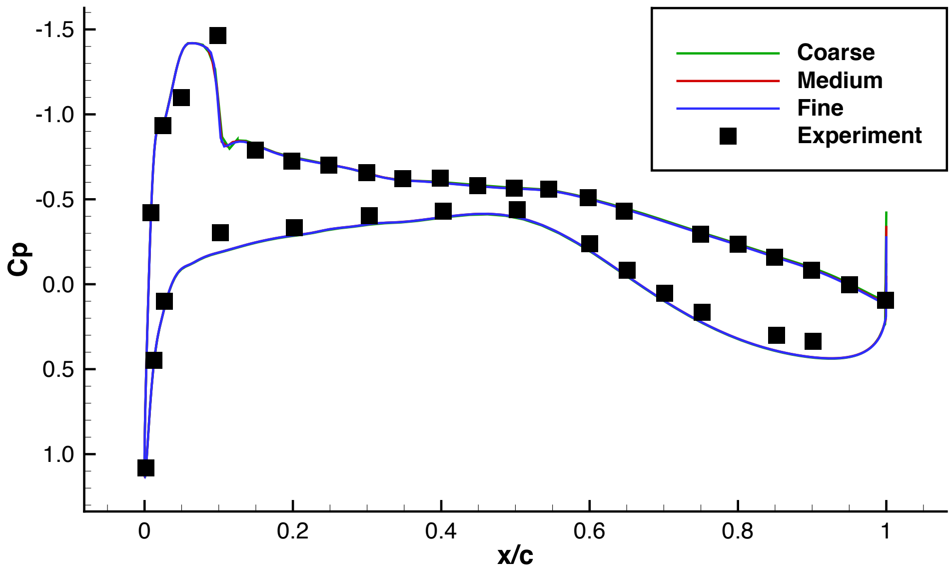


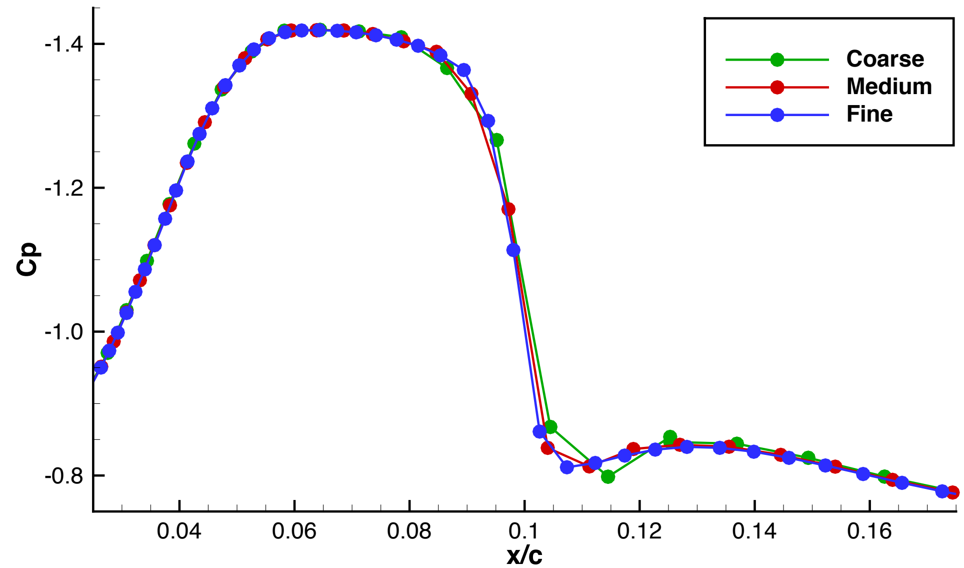


- Typical transonic flow-field is observed
- Fish-tail shock on suction-side near the leading edge
- Boundary layer increase downstream of the shock
- Steady-state force convergence is obtained in approximately 2000-3000 iterations

Case 1a: Steady-State

Cp comparison at 60 percent span

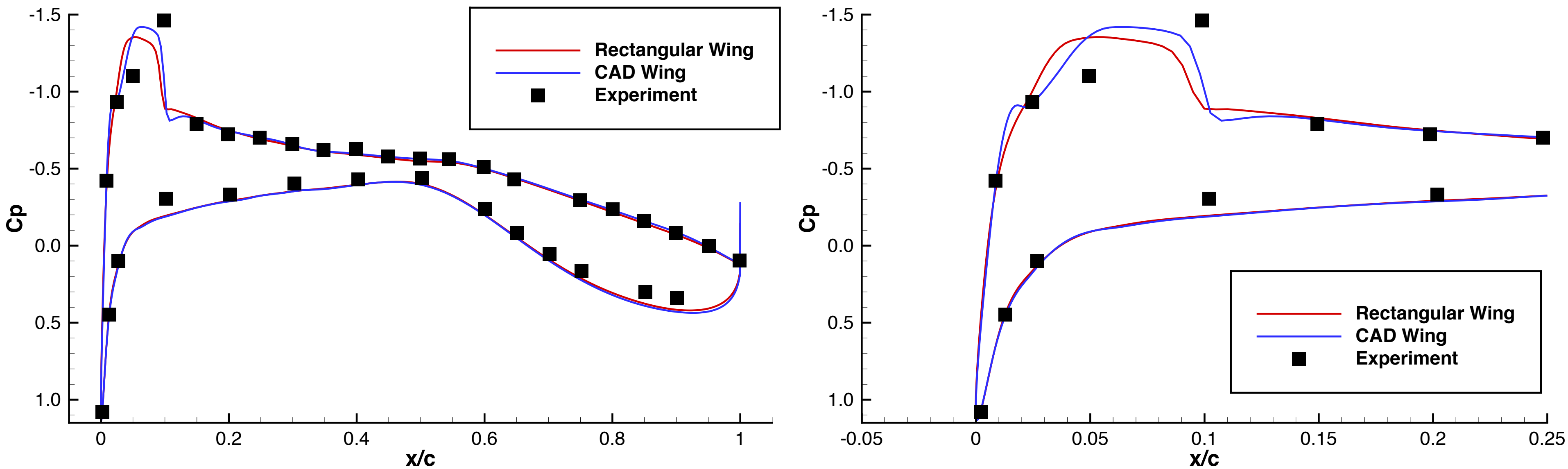




Mesh	C_L	std	C_D	std	CM_y	std
Coarse	0.4543	0.00004	0.0286	0.00003	-0.0624	0.00003
Medium	0.4497	0.00004	0.0278	0.00002	-0.0613	0.00001
Fine	0.4490	0.00005	0.0275	0.00002	-0.0611	0.00001

Case 1a: Steady-State

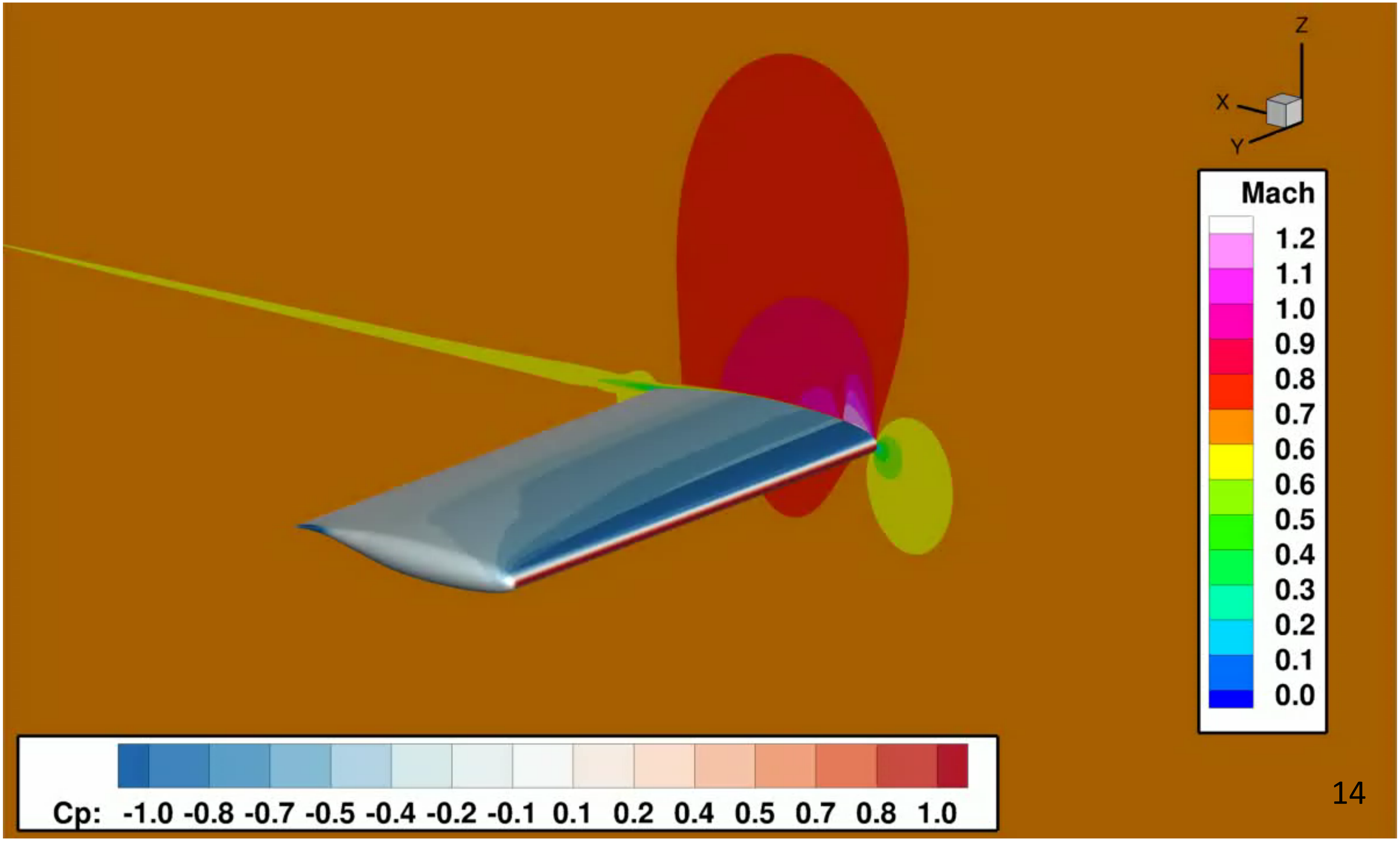
Sensitivity to geometric definition



- Minor deviations in leading edge curvature and trailing edge deflections produce a clearly observable difference in shock location
- The straight wing assumption leads to a shock forming upstream of the experimentally measured location
- This is likely caused by a difference in circulation between the straight wing and the as-built geometry
- The scanned 3D CAD should be used directly for grid generation

Case 1b: Forced Pitch

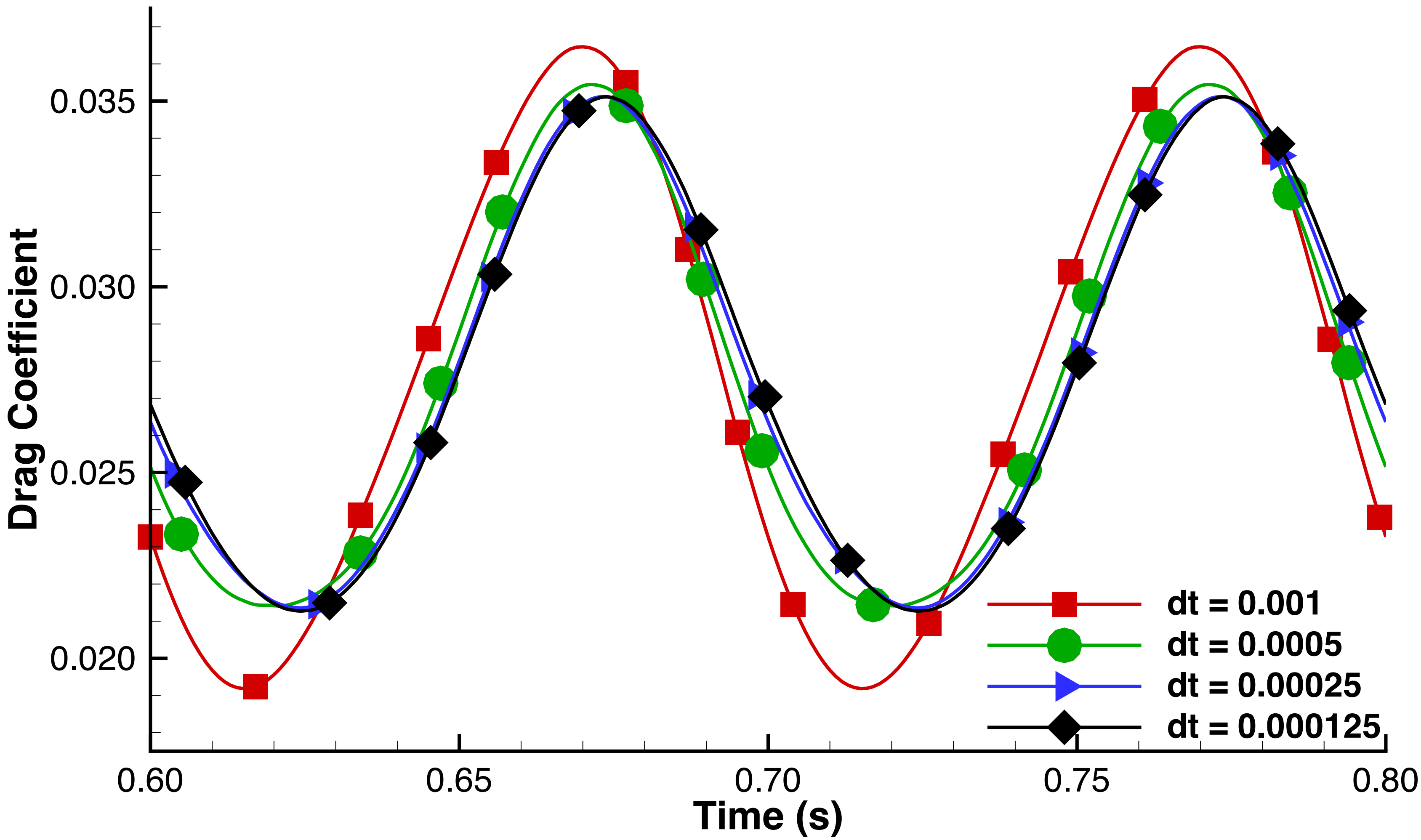
Mach: 0.7 Re: 4.56 million (chord) AOA: 3° Forced Pitch: 10 Hz and 1°



Case 1b: Forced Pitch

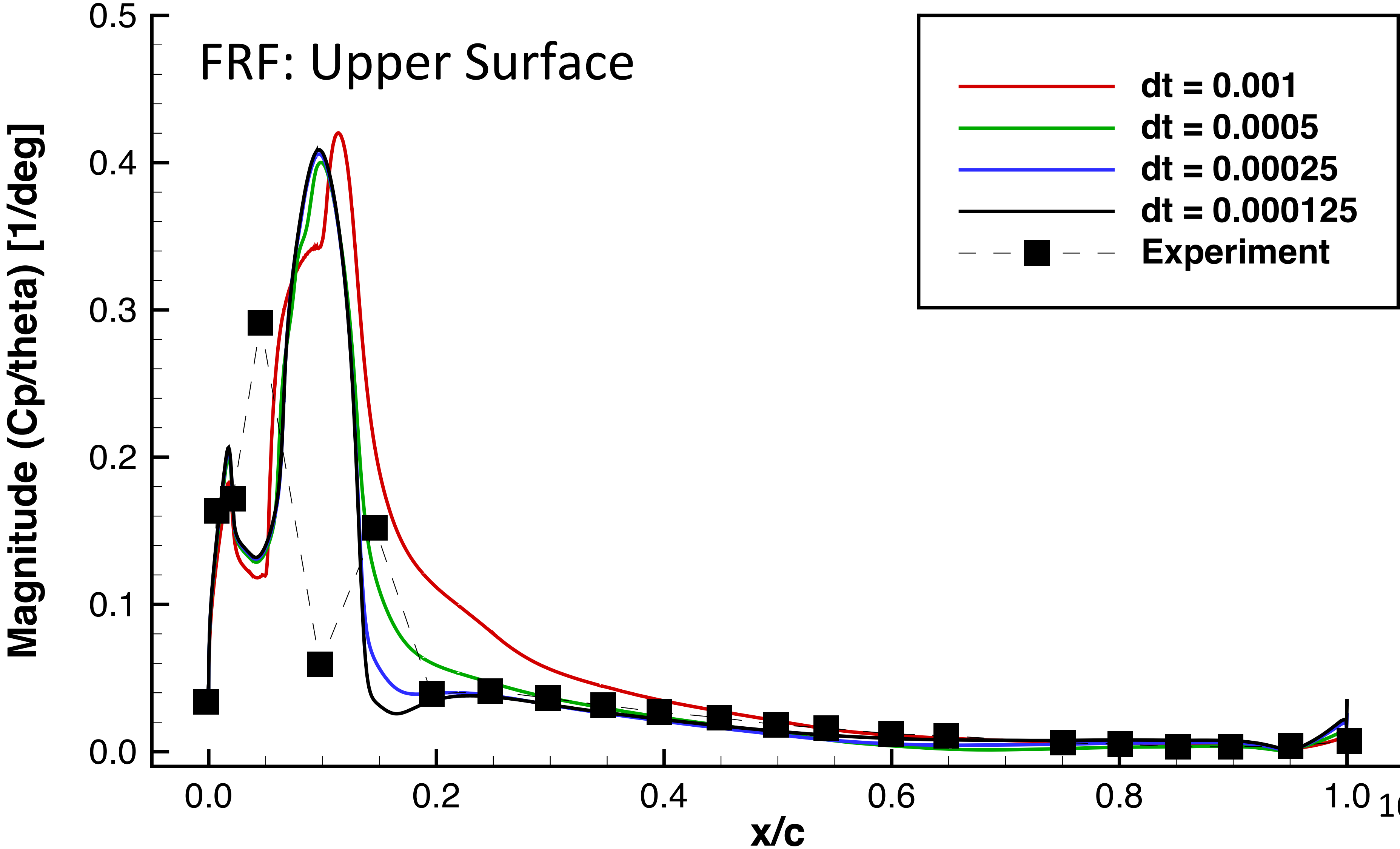
Time-step sensitivity study on Very-Fine mesh

- Four time-steps considered: 100 to 800 steps per period
- Sub-iterations held fixed at 10 (at least 2 orders of magnitude residual reduction)



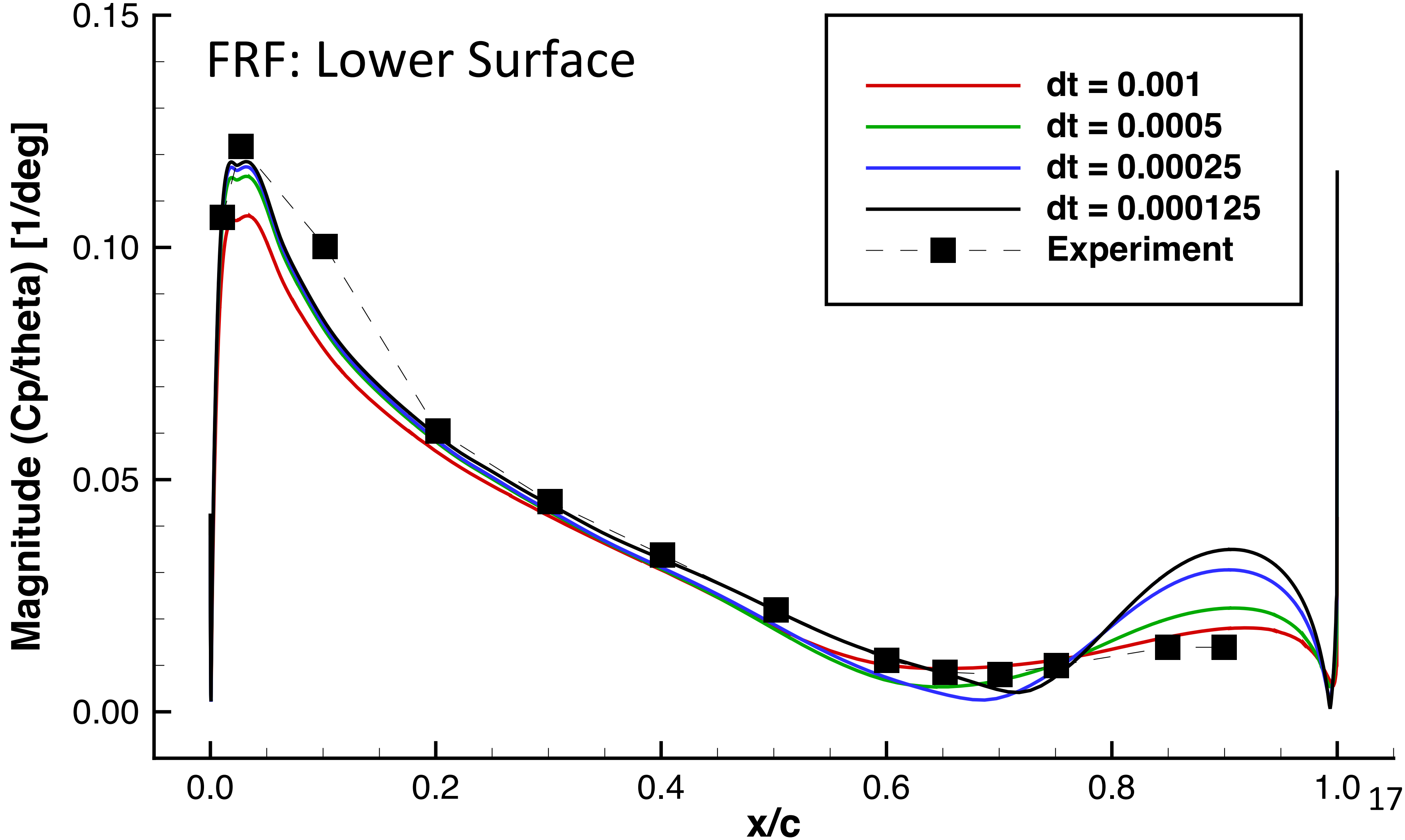
Case 1b: Forced Pitch

Time-step sensitivity study on Very-Fine mesh



Case 1b: Forced Pitch

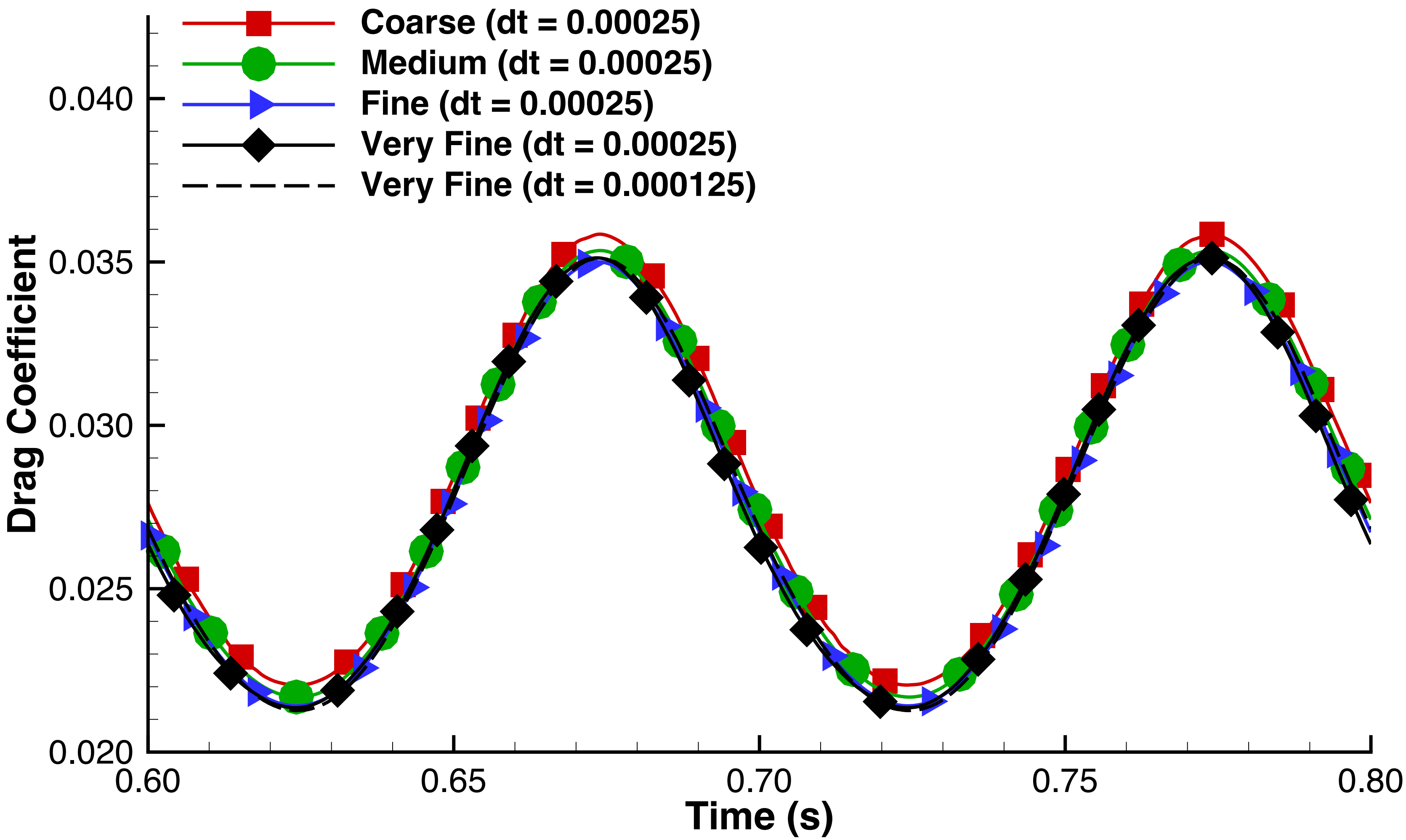
Time-step sensitivity study on Very-Fine mesh



Case 1b: Forced Pitch

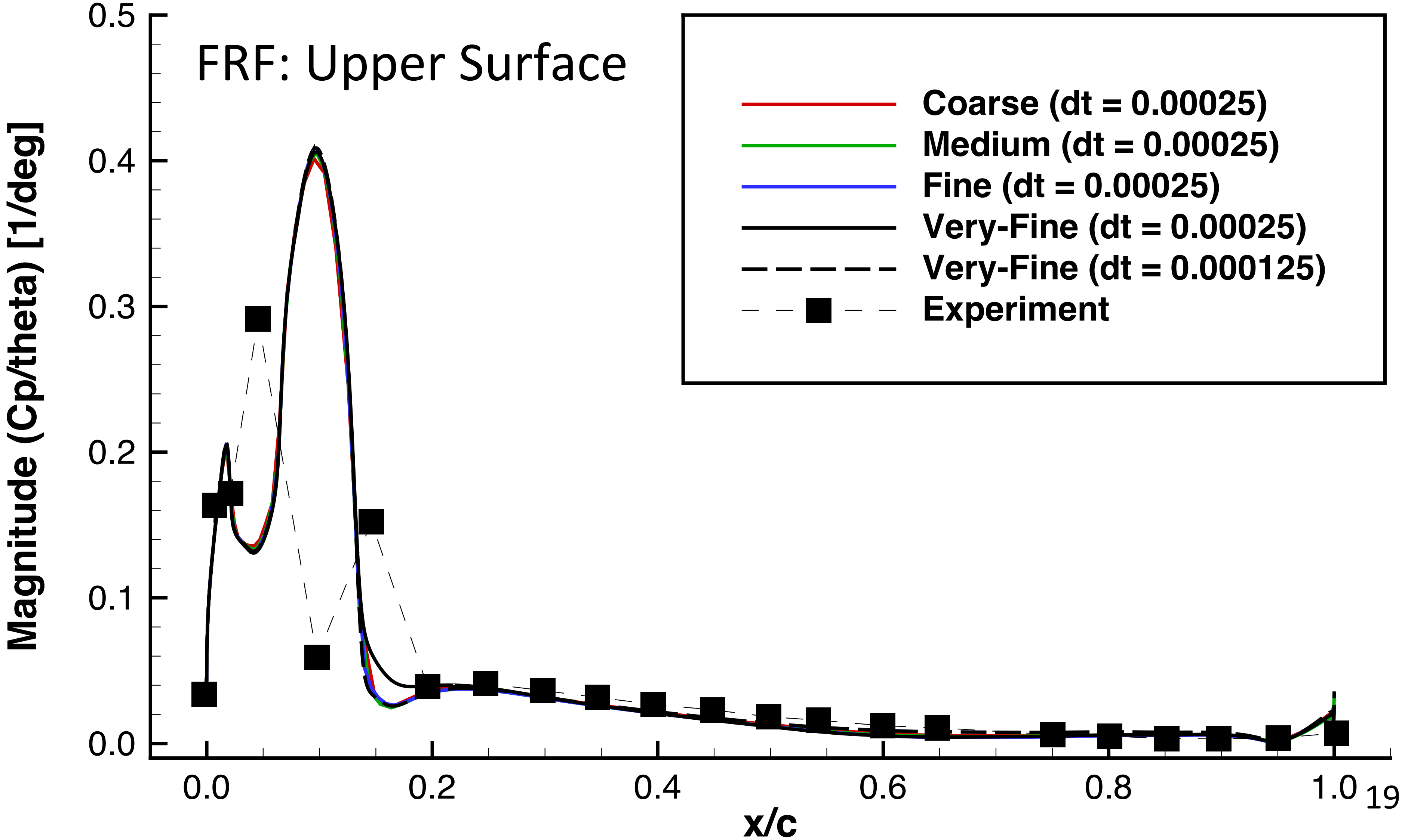
Mesh sensitivity study

- Four mesh resolutions considered each ran with a time-step of 0.00025 and compared with the very-fine mesh result using dt = 0.000125



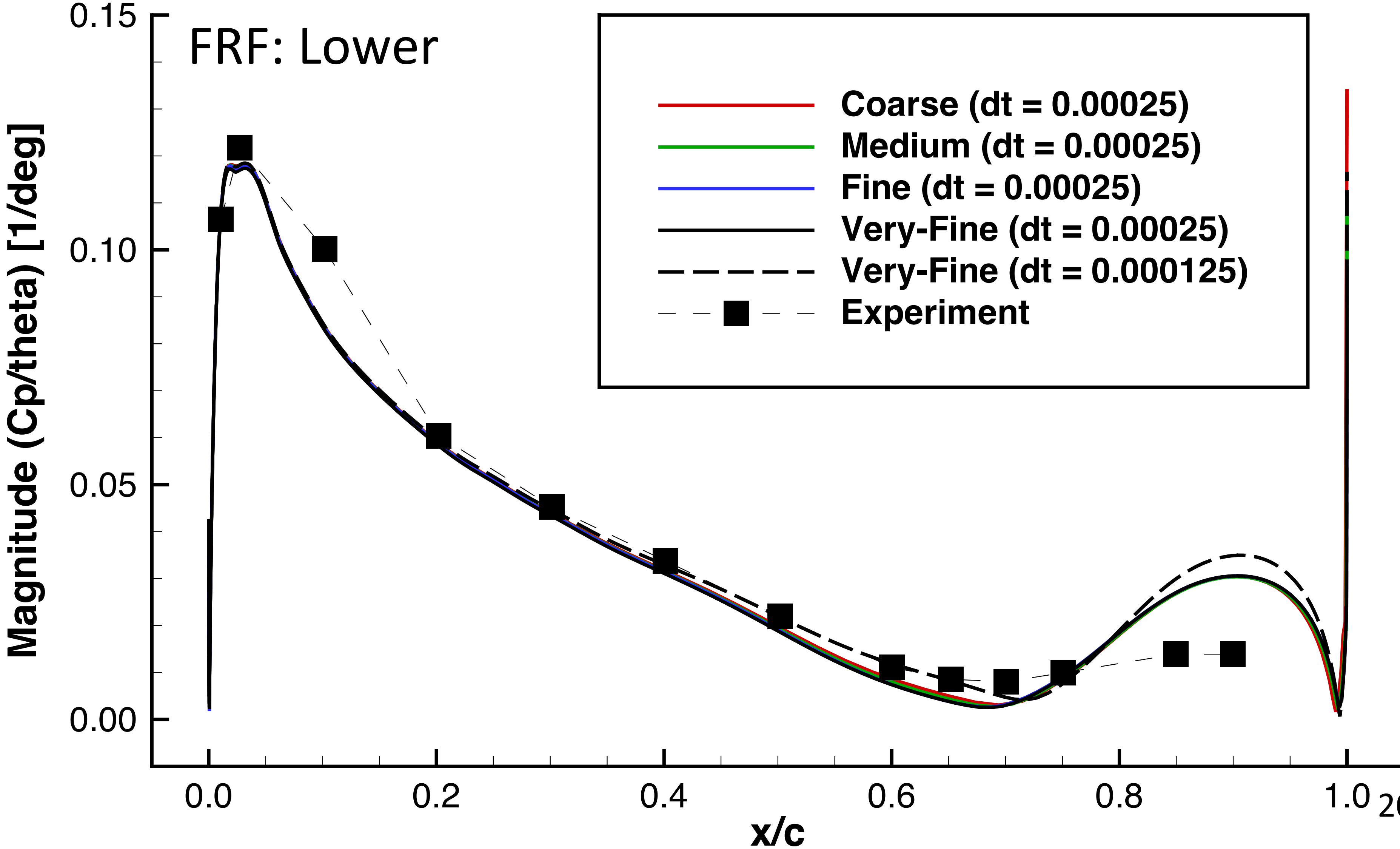
Case 1b: Forced Pitch

Mesh sensitivity study



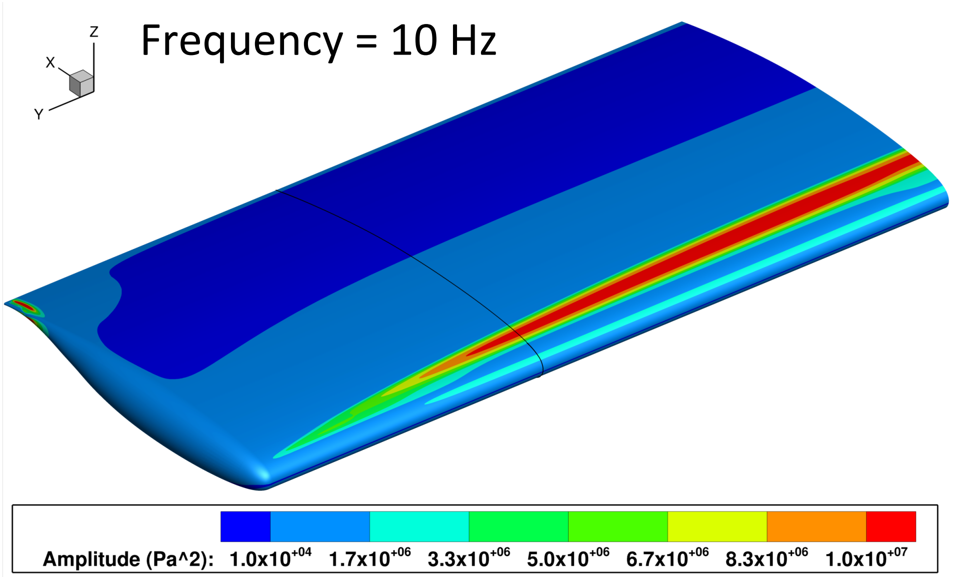
Case 1b: Forced Pitch

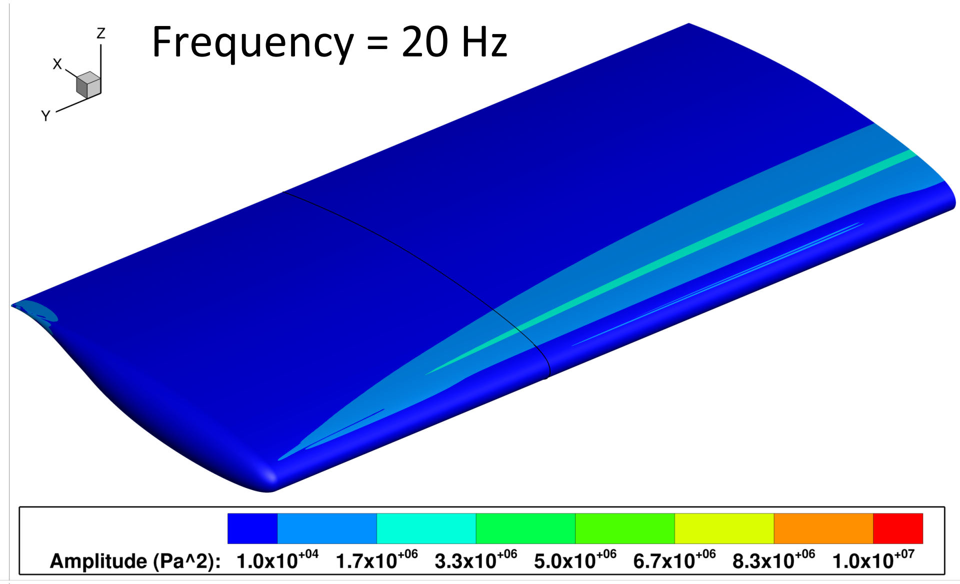
Mesh sensitivity study

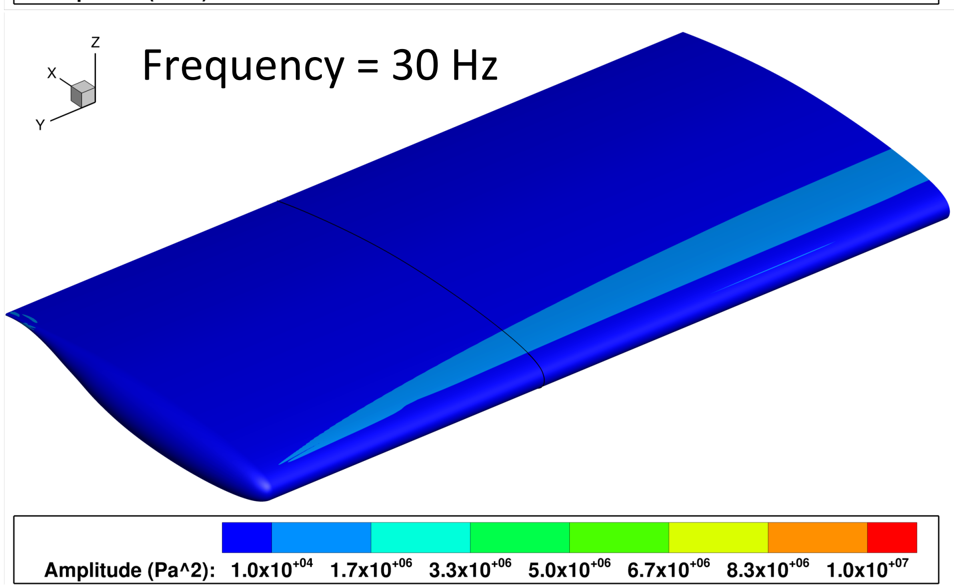


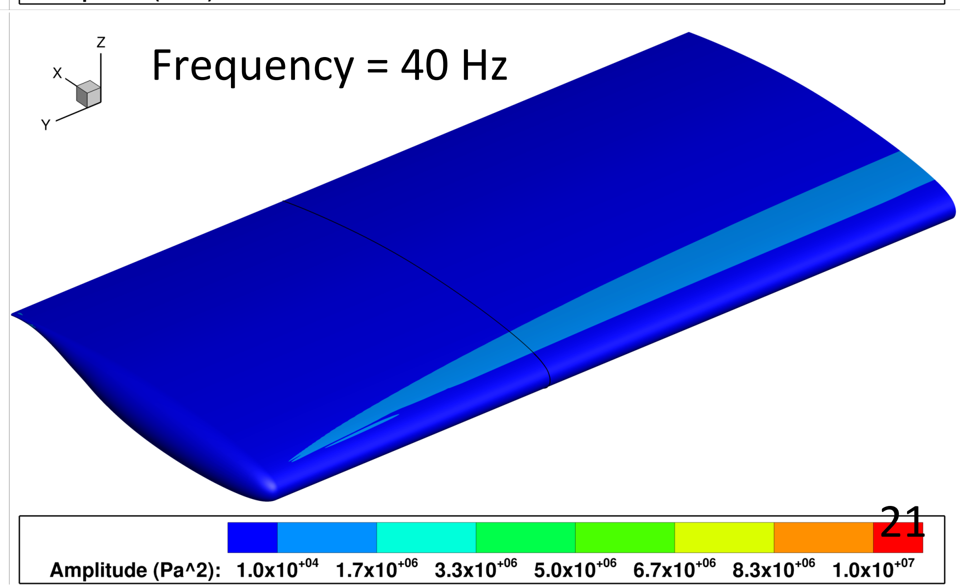
Case 1b: Forced Pitch

Frequency domain analysis





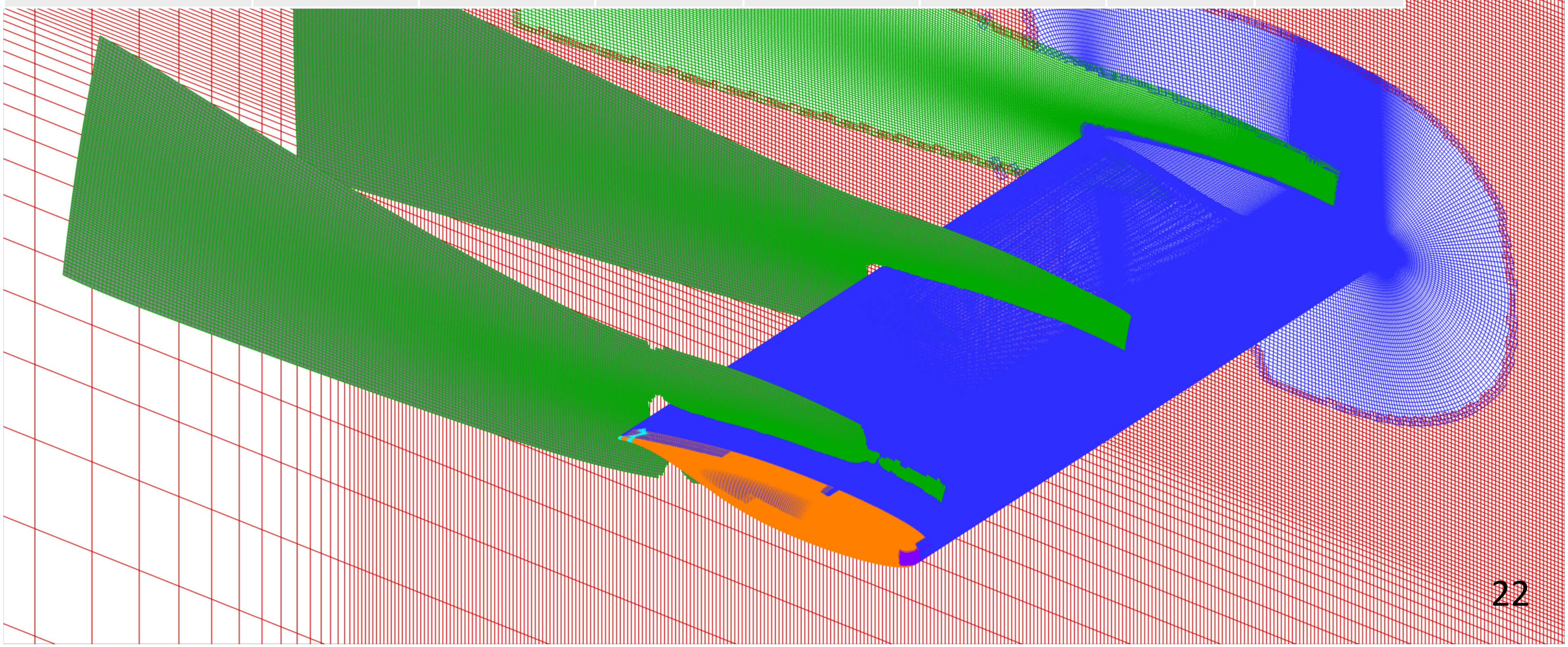




Structured Overset Grid System

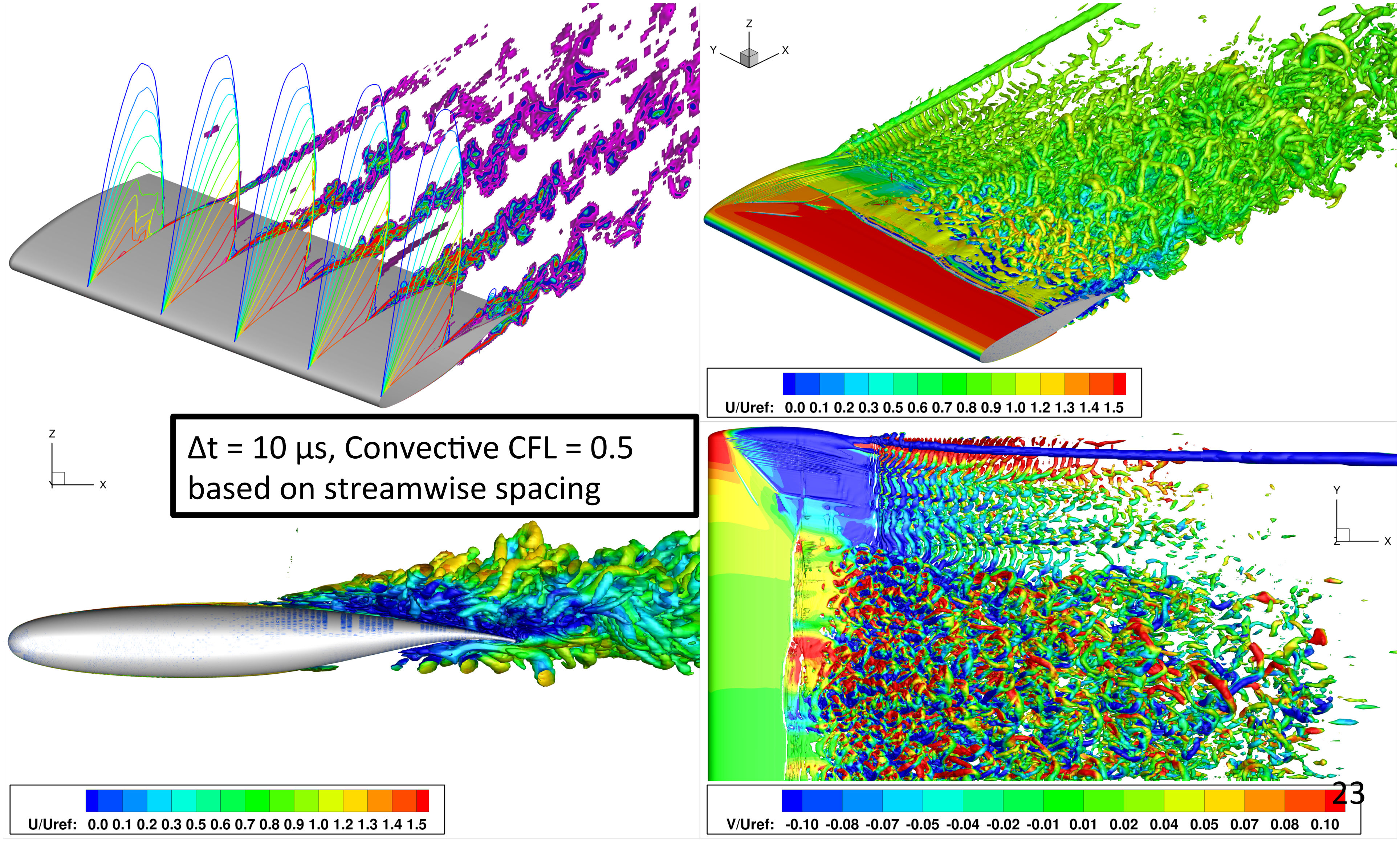
Ultra-Fine Grid1 for Delayed Detached Eddy Simulation (DDES)

Mesh	Points ($x10^6$)	Wall (mm)	LE (mm)	TE (mm)	Stream (mm)	Span (mm)	Tip (mm)
UFG1	99.1	0.0020	0.27	0.1625	5	2.5	0.535
Wall Units		1	135	81.25	2500	1250	267.5



Case 3a: Shock/BL Separation

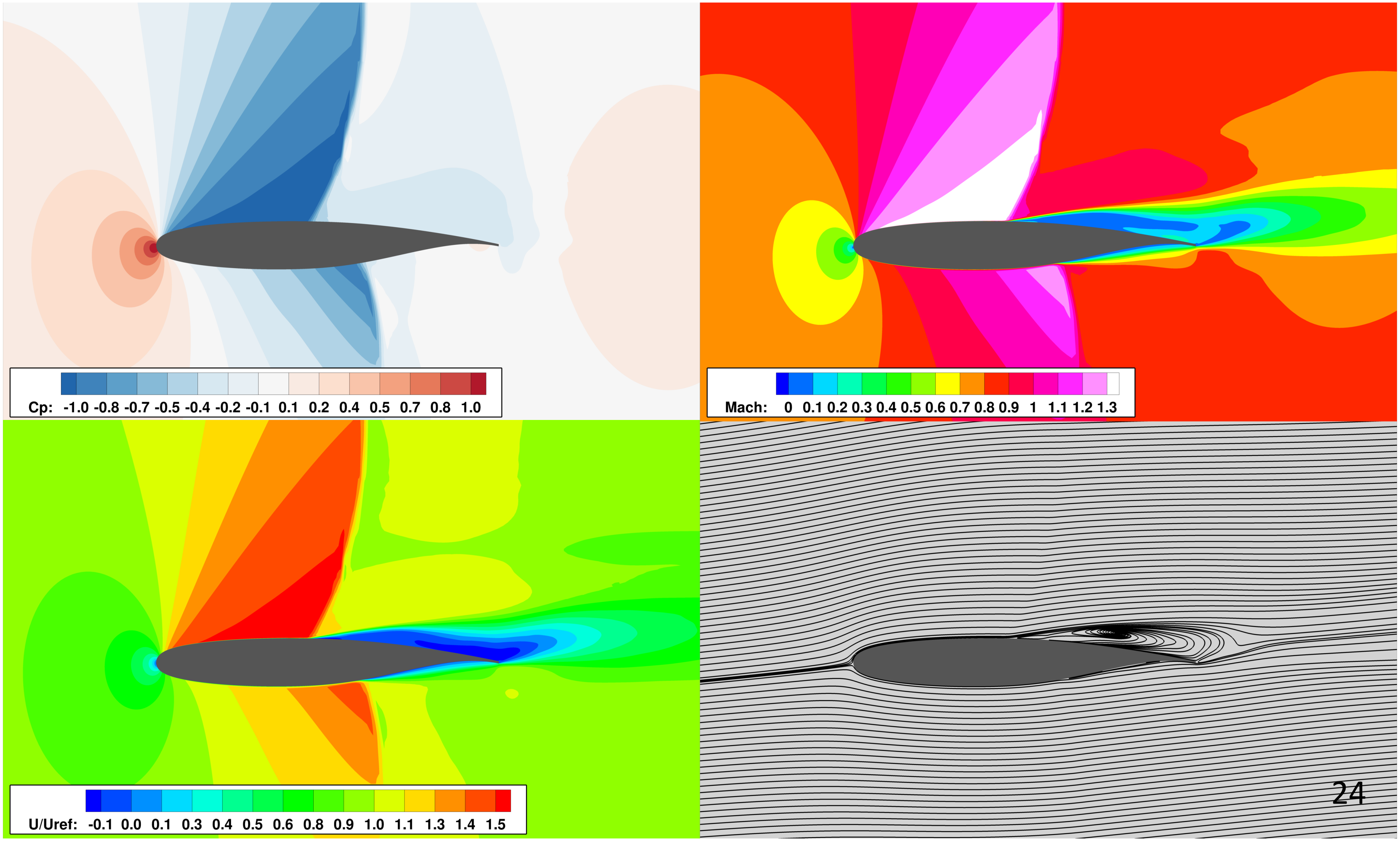
Mach: 0.85 Reynolds Number: 4.49 million (chord) AOA: 5 degrees



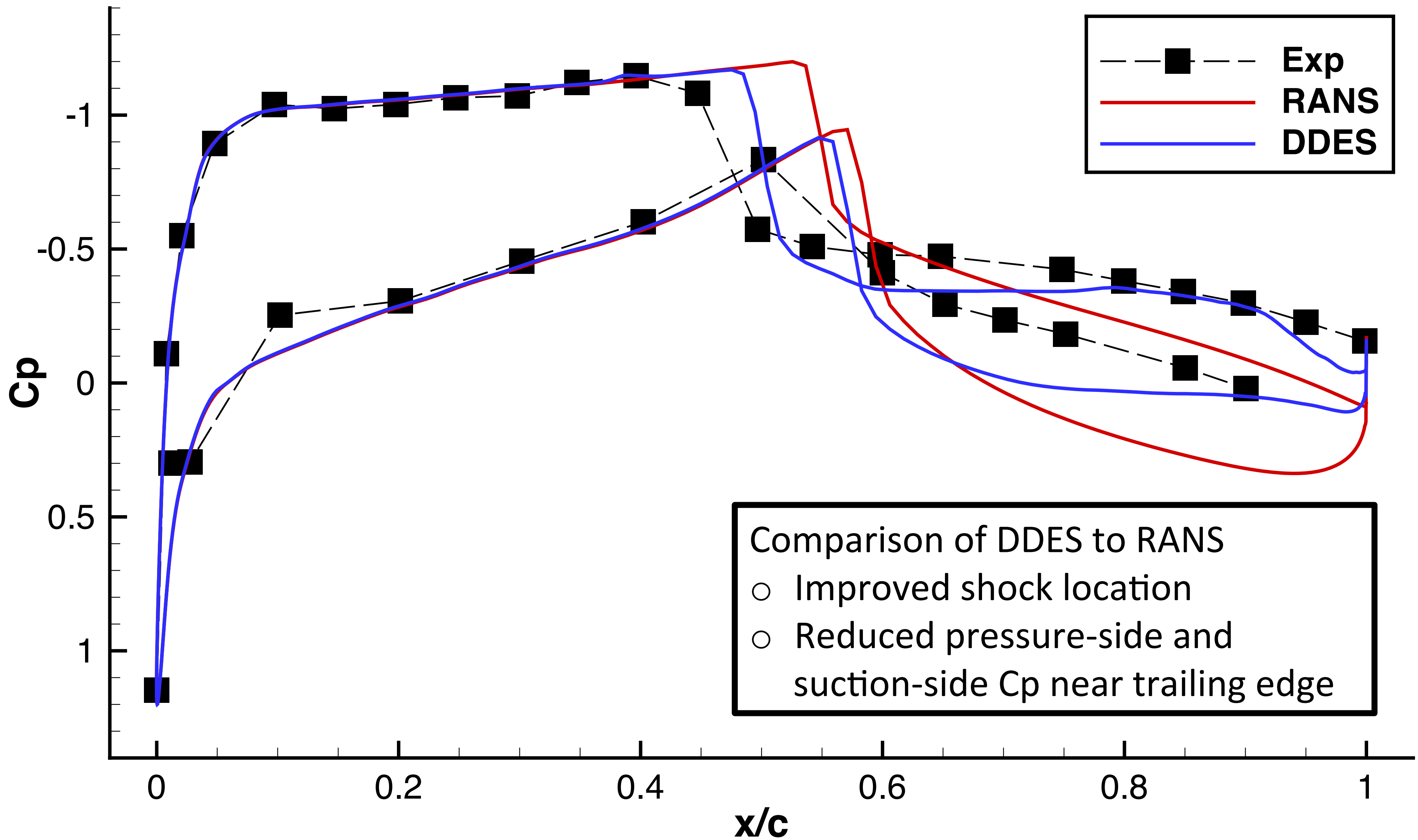
Δt = 10 μs, Convective CFL = 0.5
based on streamwise spacing

Case 3a: Shock/BL Separation

Contour plots of time-averaged flow-field on symmetry plane



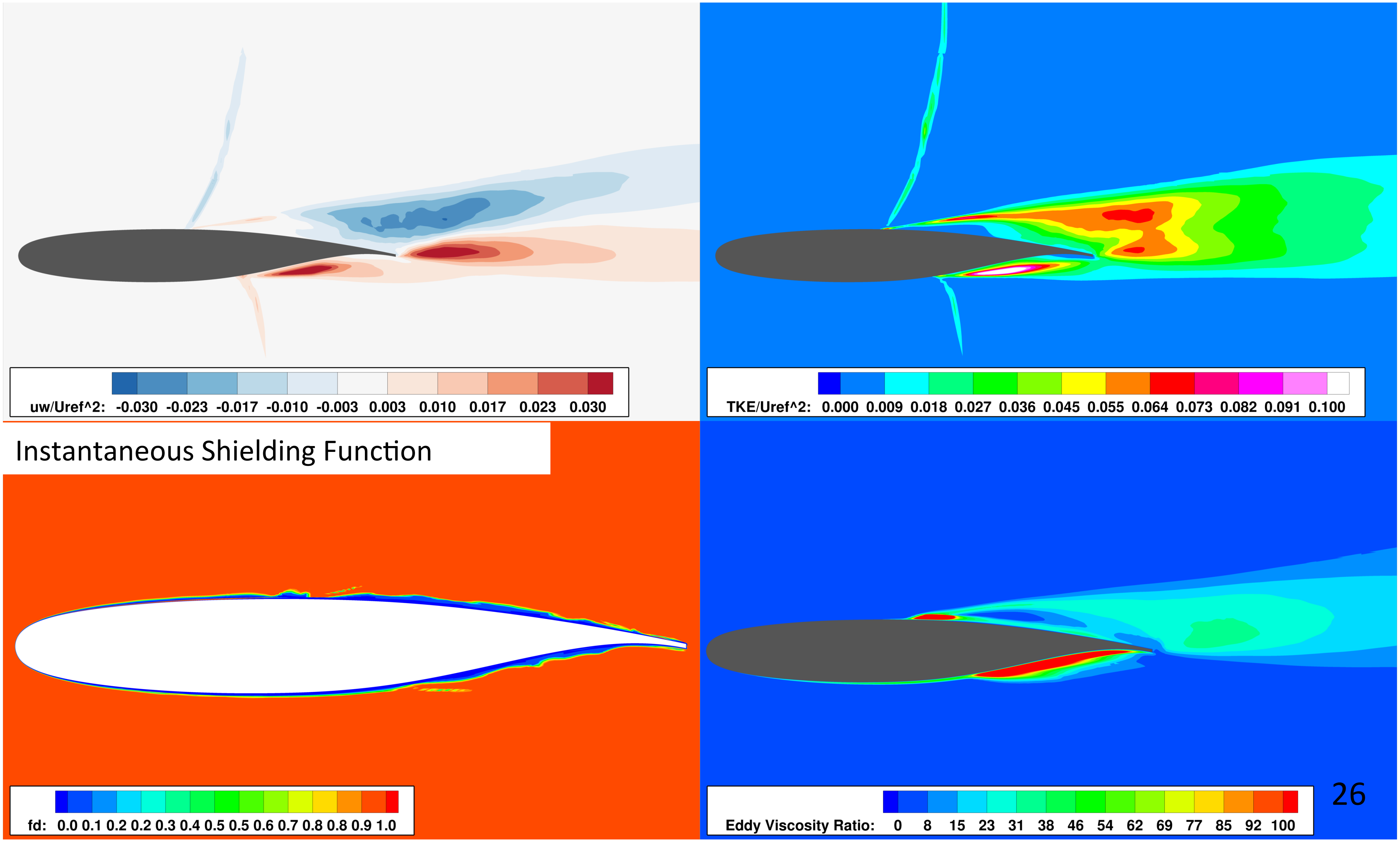
Case 3a: Shock/BL Separation



Cp comparison at 60 percent span

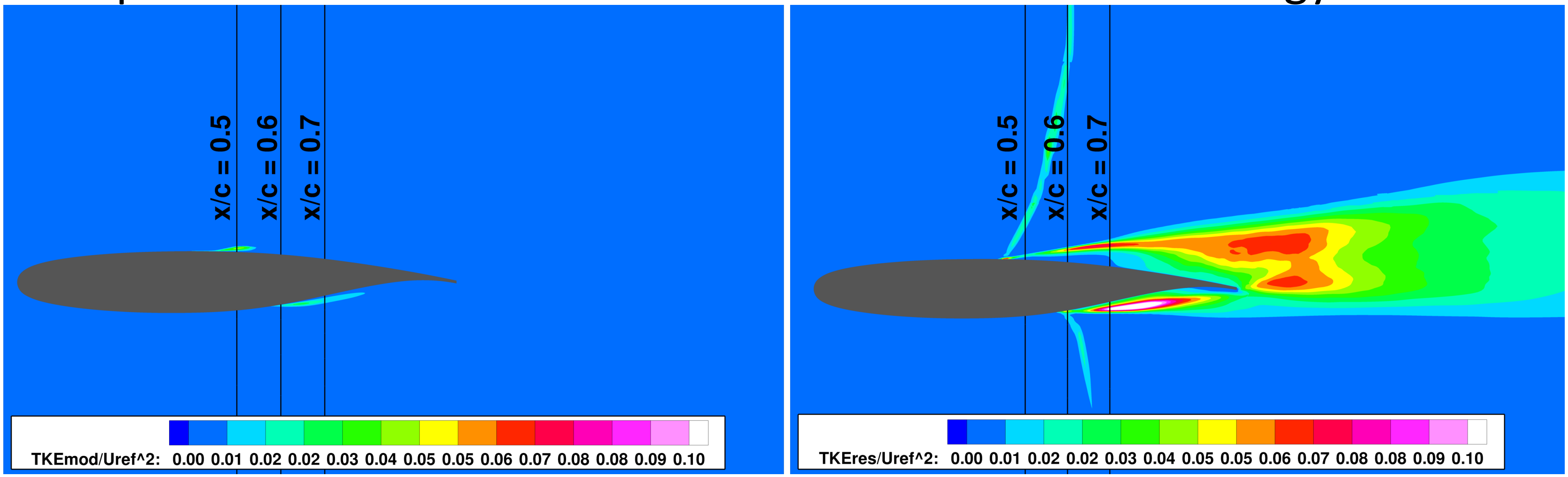
Case 3a: Shock/BL Separation

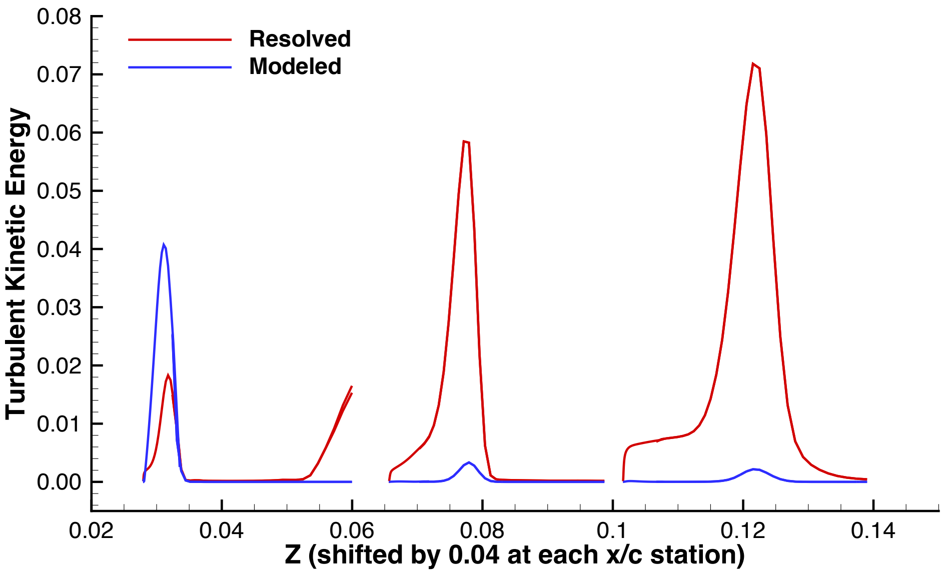
Contour plots of turbulent statistics and model quantities



Case 3a: Shock/BL Separation

Comparison of modeled and resolved turbulent kinetic energy

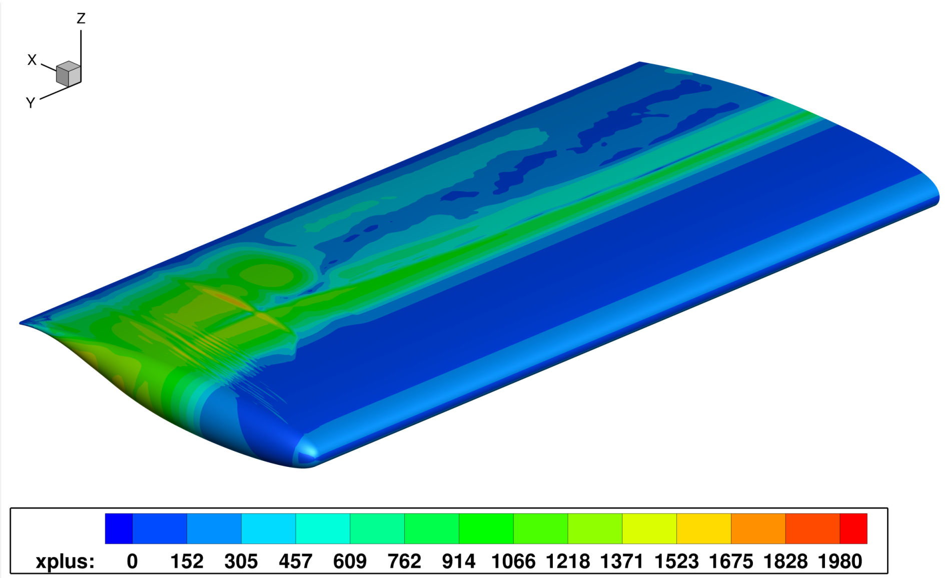


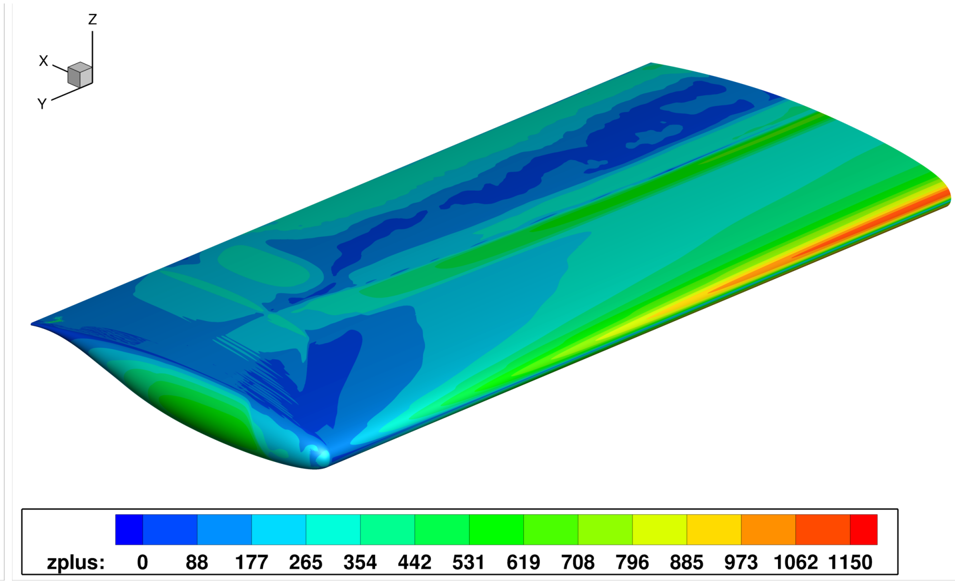


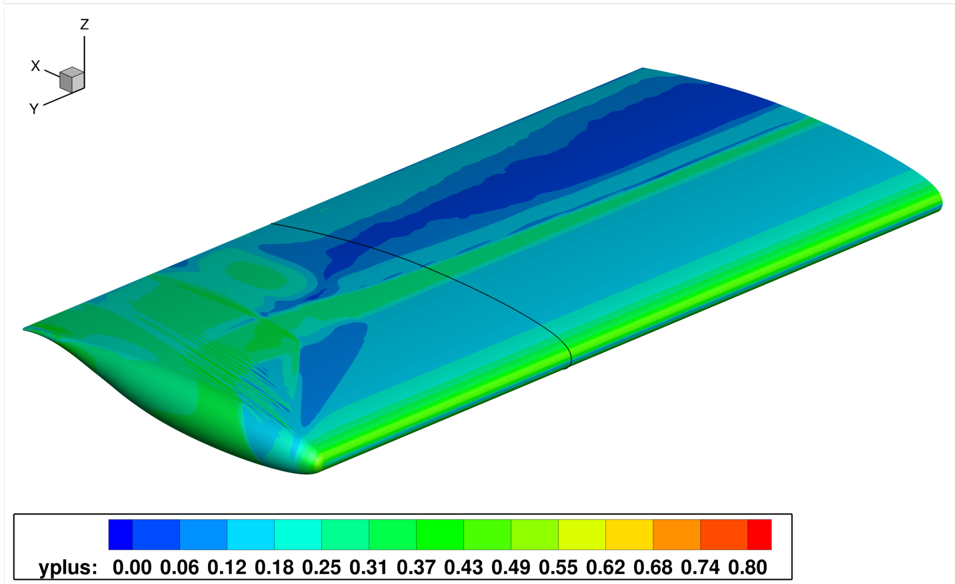
- Just downstream of the shock (x/c = 0.5) the modeled TKE is more than a factor of two larger than the resolved TKE delaying the development of 3D turbulent structures in the separated flow region
- Further downstream (x/c = 0.6 and 0.7) the resolved TKE increases while the modeled TKE vanishes

Case 3a: Shock/BL Separation

Realized Grid Resolution in Viscous Wall Units



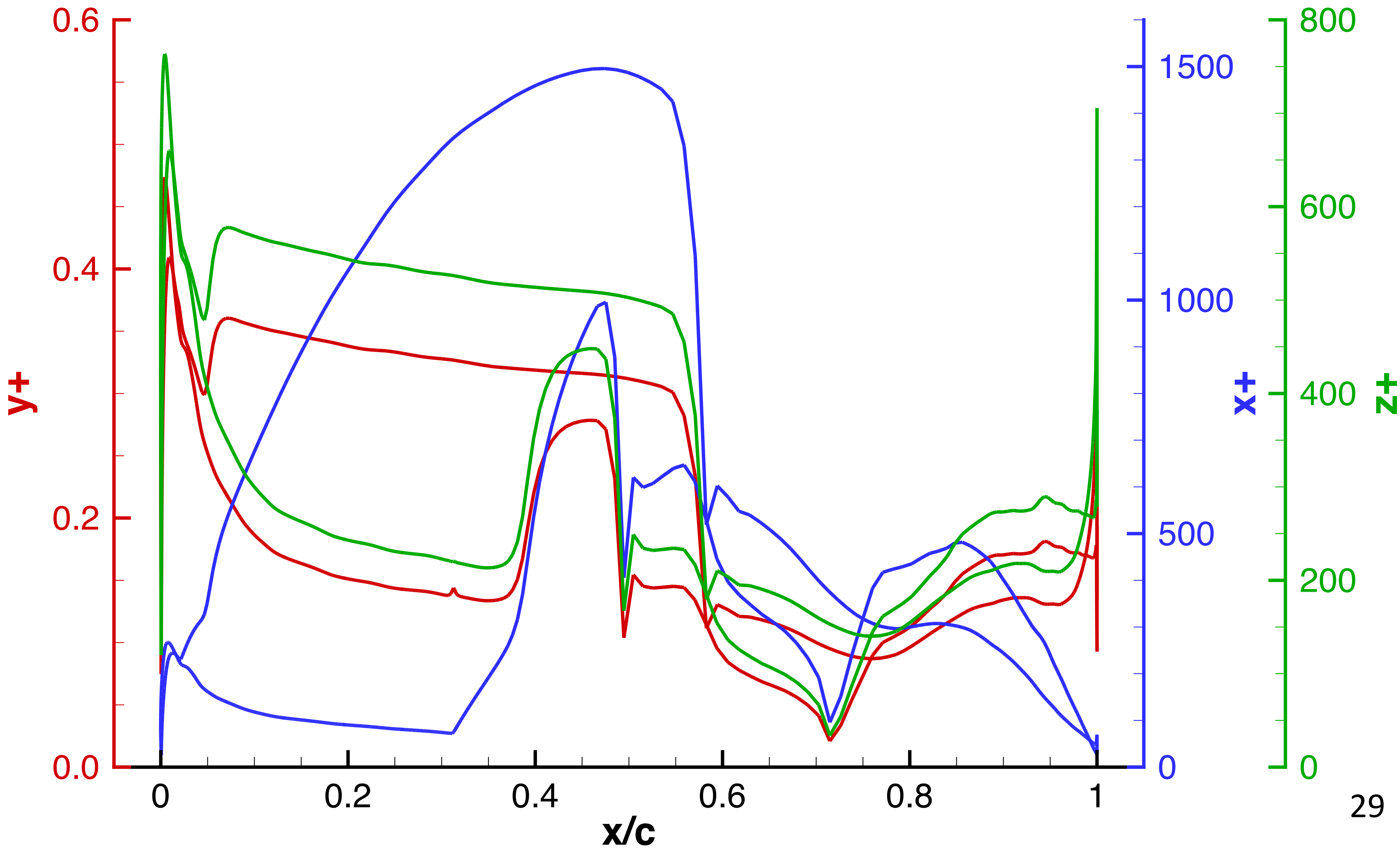




- Maximum x+ ≈ 1980, y+ ≈ 0.76, z+ ≈ 1150
- Z+ is large near the leading and trailing edges since the spanwise spacing is relatively uniform while the streamwise spacing is clustered
- A large value in all three directions is observed just upstream of the shock before the flow separates

Case 3a: Shock/BL Separation

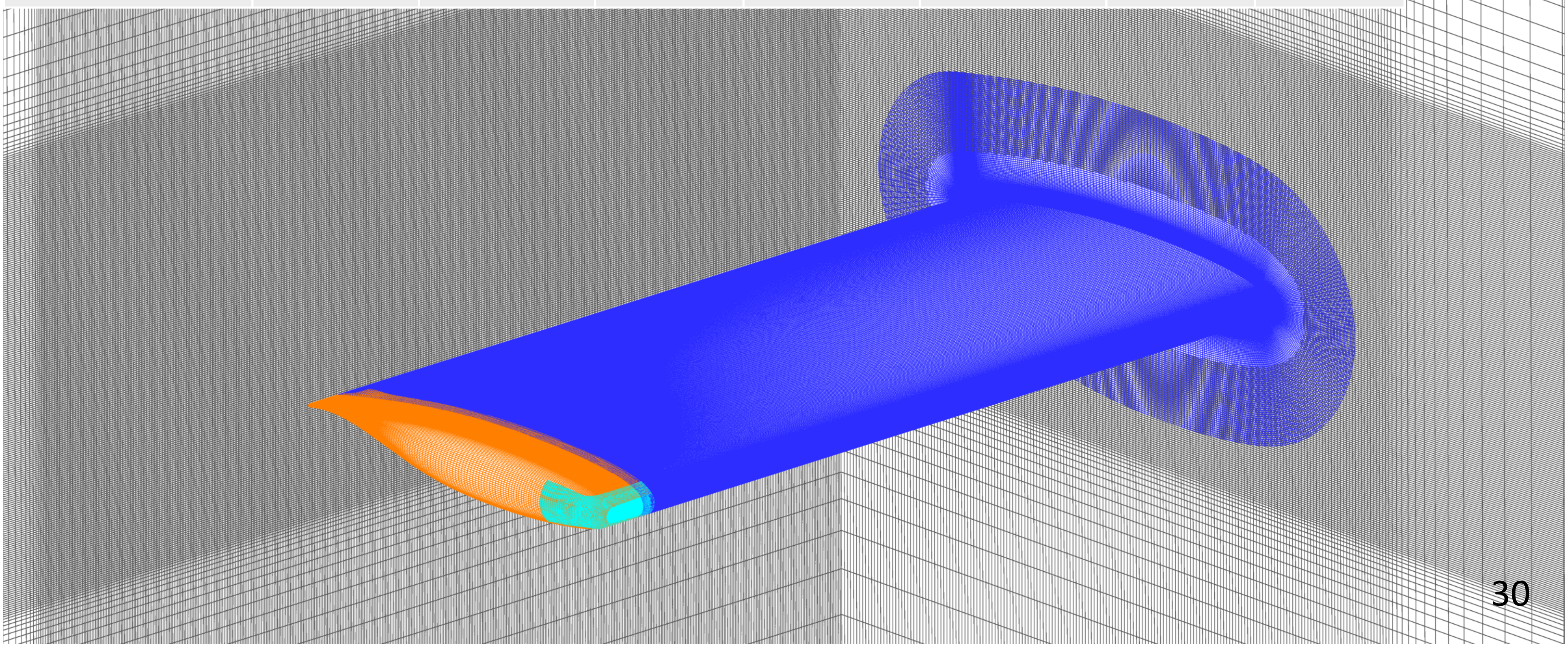
Realized Grid Resolution in Viscous Wall Units at 60% span



Structured Overset Grid System

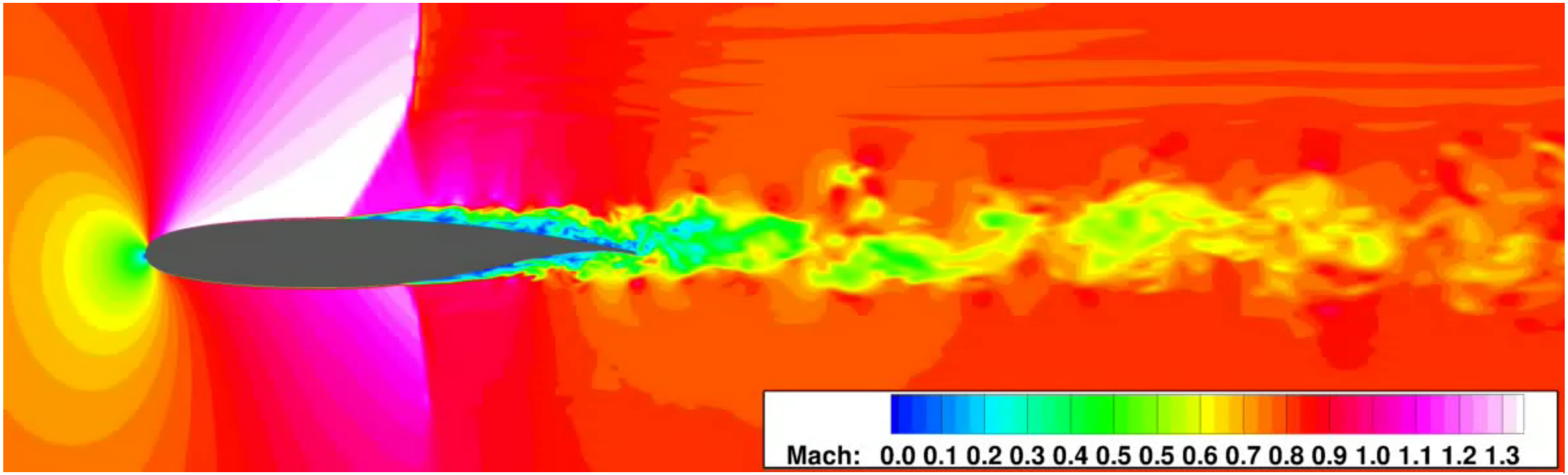
Ultra-Fine Grid2 for Hybrid RANS/LES Analysis

Mesh	Points ($x10^6$)	Wall (mm)	LE (mm)	TE (mm)	Stream (mm)	Span (mm)	Tip (mm)
UFG2	159.2	0.0020	0.27	0.1625	4	2	0.535
Wall Units		1	135	81.25	2000	1000	267.5

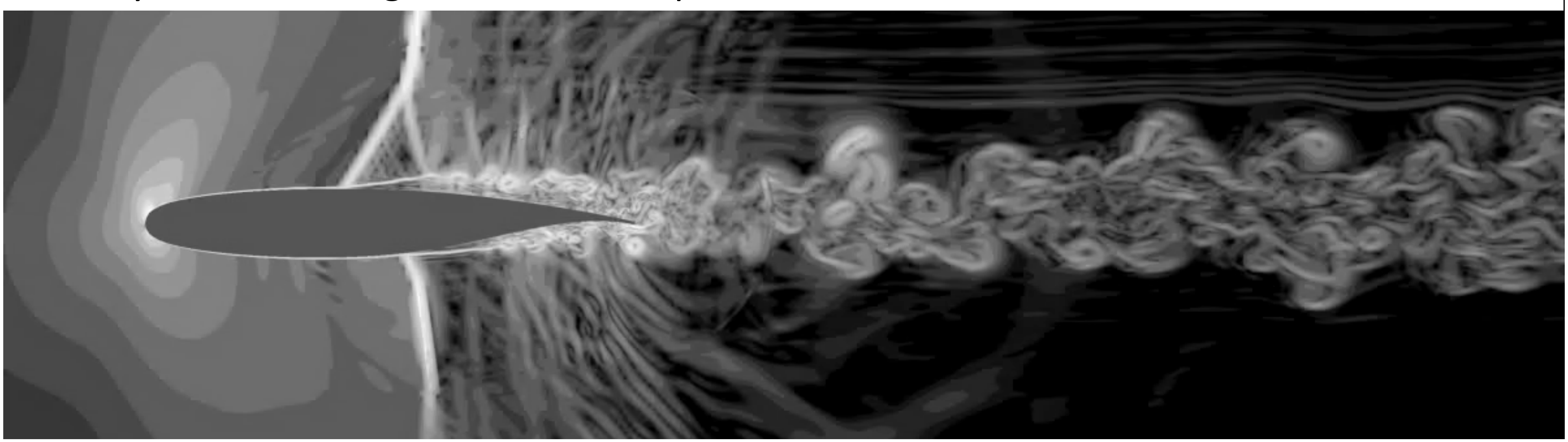


Case 3a: Shock/BL Separation

Mach at 60% span

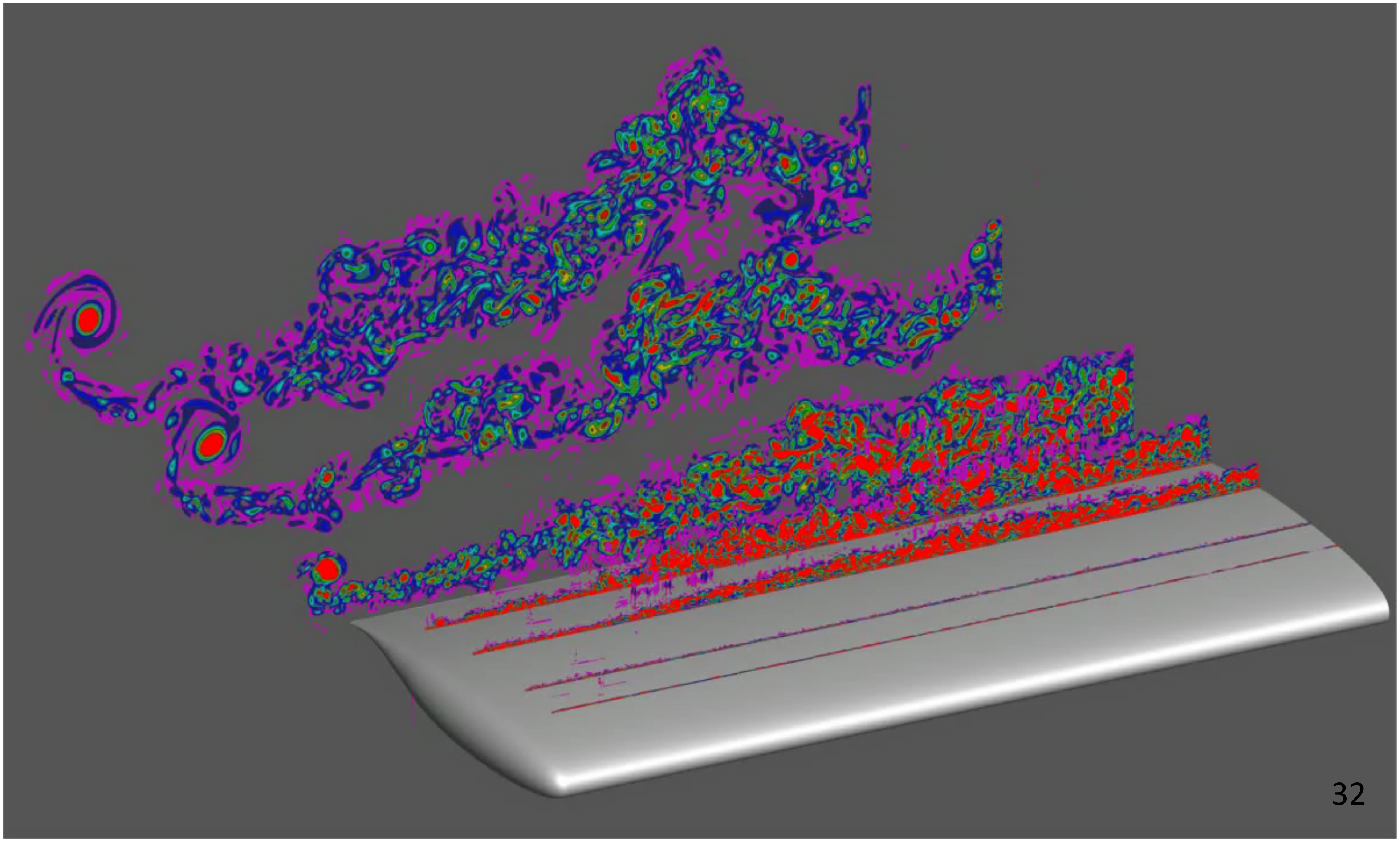


Density Gradient Magnitude at 60% span



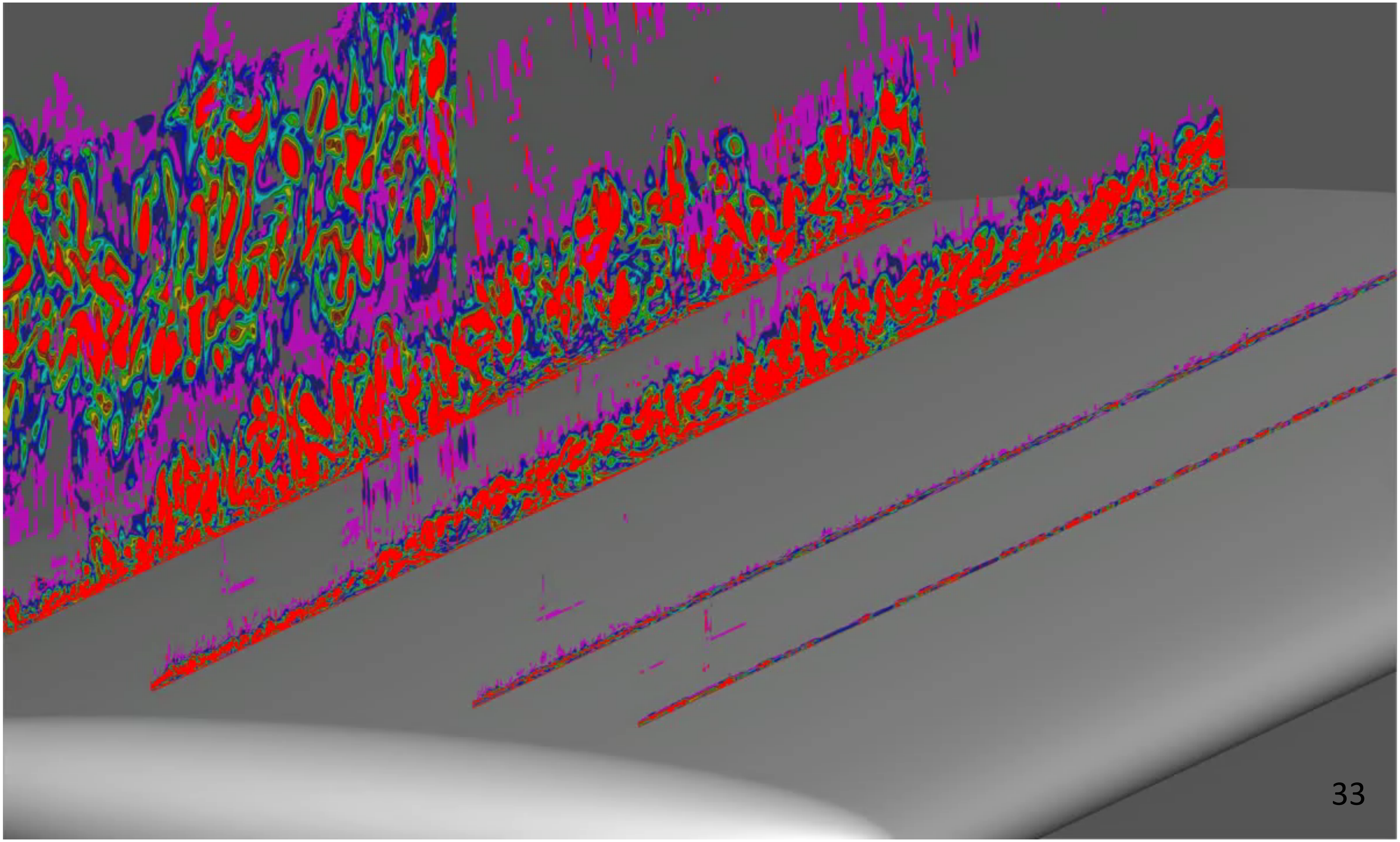
Case 3a: Shock/BL Separation

Streamwise Voticity Magnitude at several streamwise stations

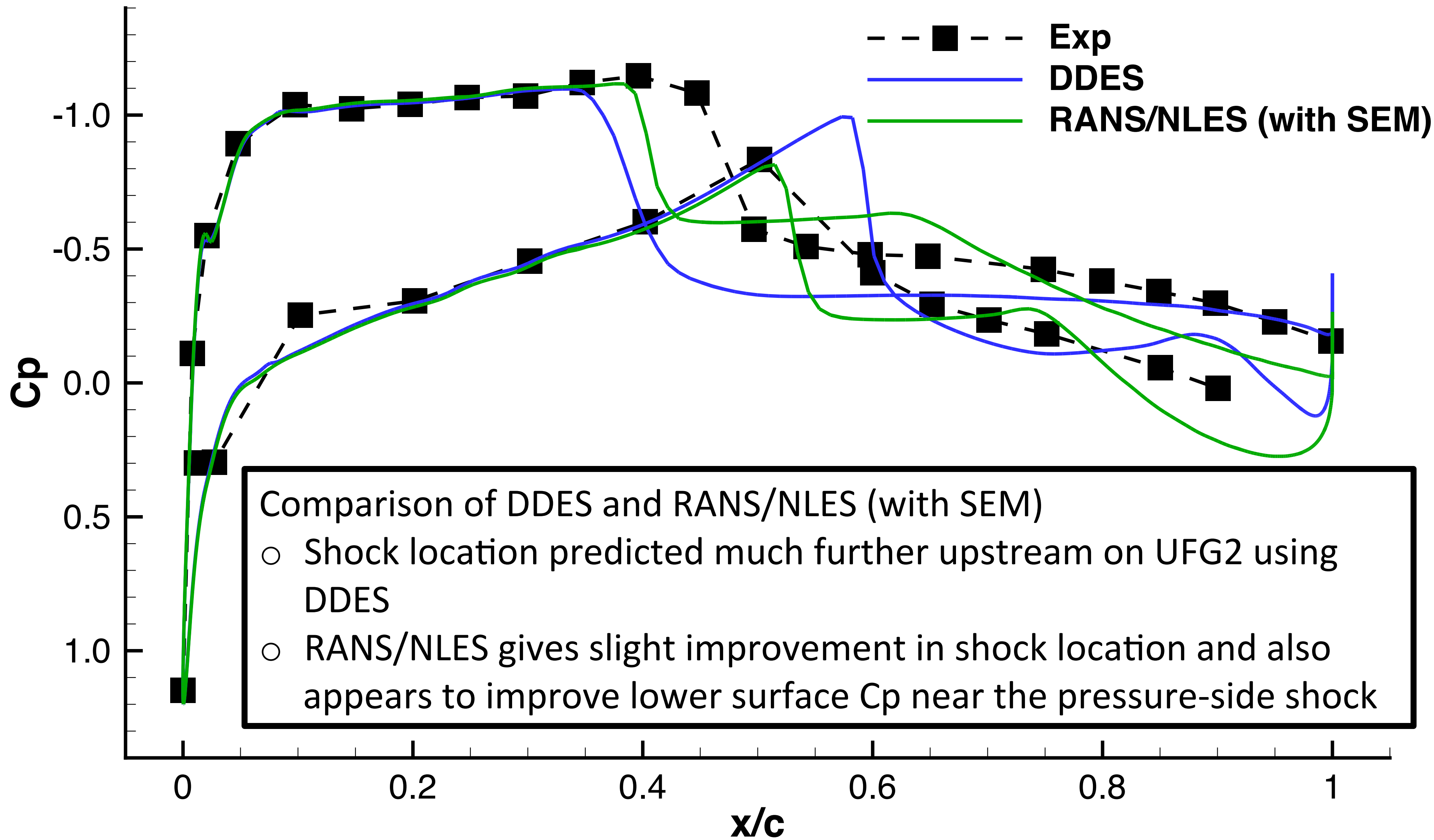


Case 3a: Shock/BL Separation

Close-up of Streamwise Vorticity Magnitude near the surface



Case 3a: Shock/BL Separation

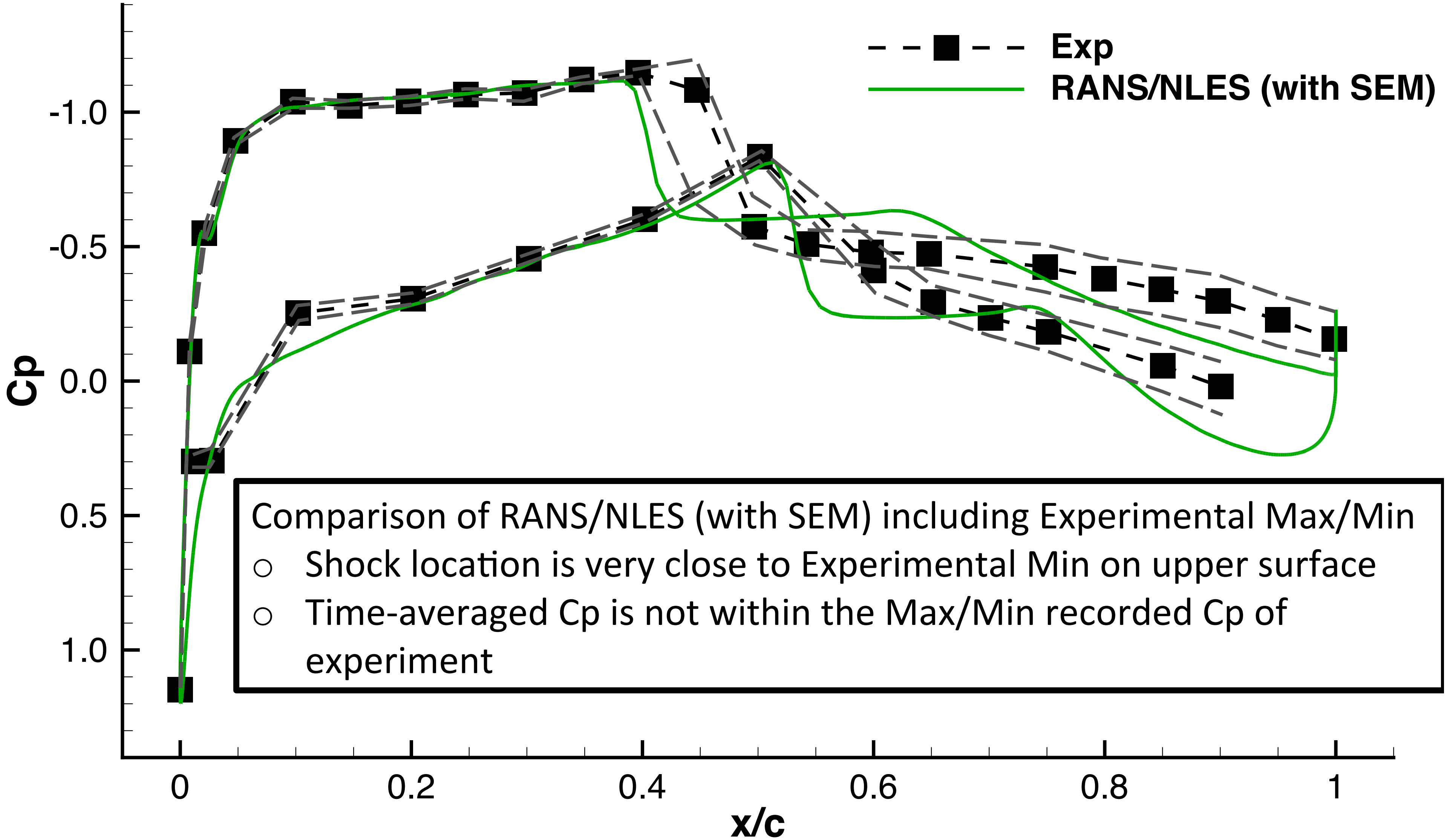


Comparison of DDES and RANS/NLES (with SEM)

- Shock location predicted much further upstream on UFG2 using DDES
- RANS/NLES gives slight improvement in shock location and also appears to improve lower surface Cp near the pressure-side shock

Cp comparison at 60 percent span

Case 3a: Shock/BL Separation



Comparison of RANS/NLES (with SEM) including Experimental Max/Min

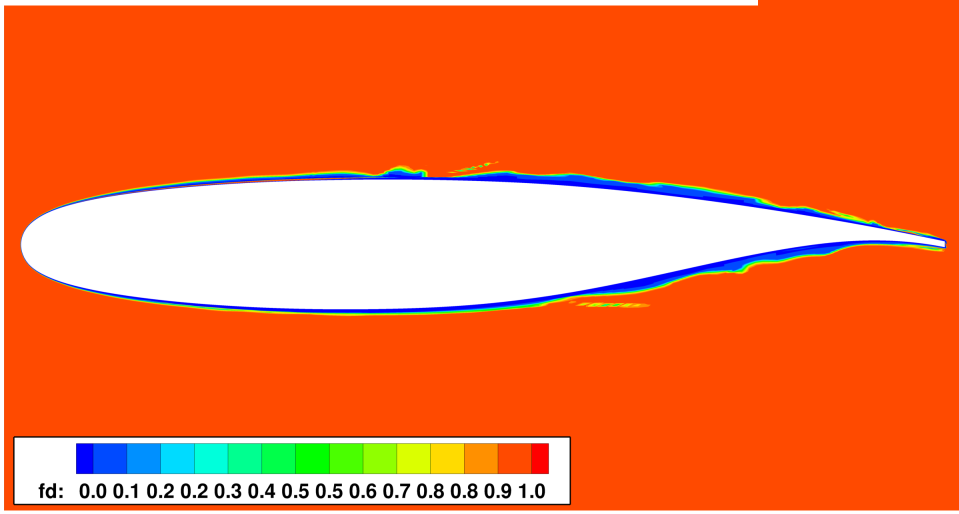
- Shock location is very close to Experimental Min on upper surface
- Time-averaged Cp is not within the Max/Min recorded Cp of experiment

Cp comparison at 60 percent span

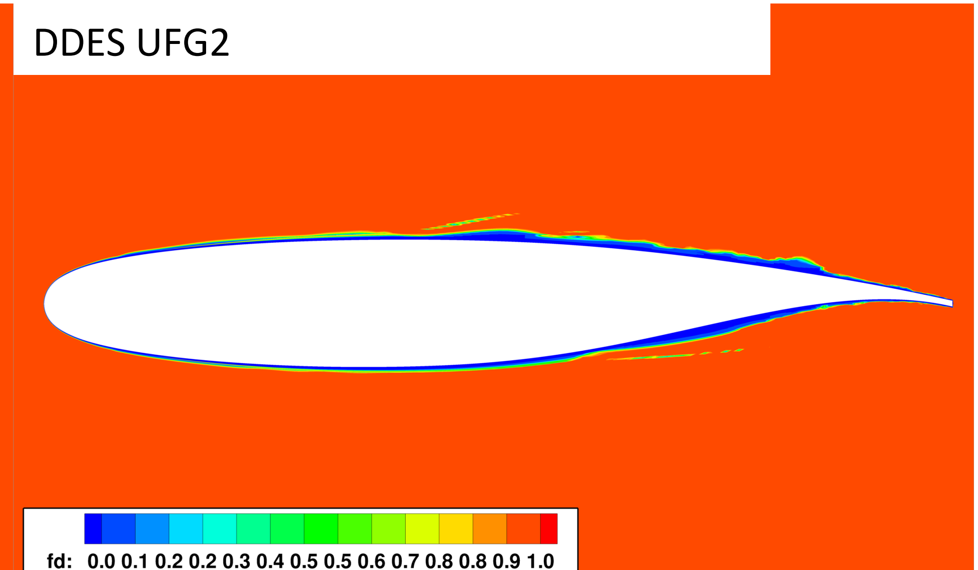
Case 3a: Shock/BL Separation

Comparison of Instantaneous Shielding Function (RANS/LES interface)

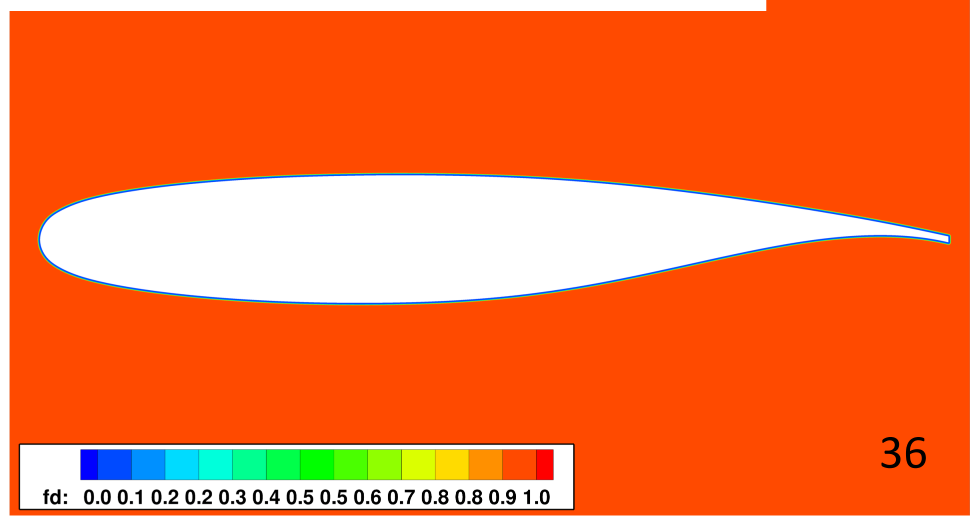
DDES UFG1



DDES UFG2



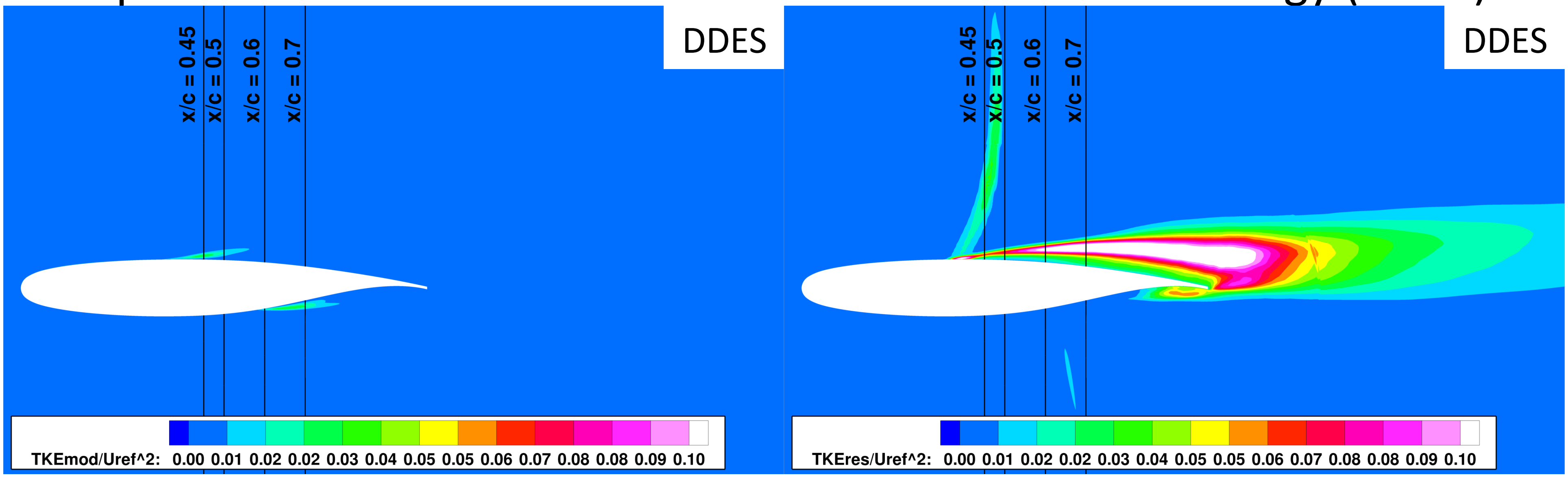
RANS/NLES (with SEM) UFG2

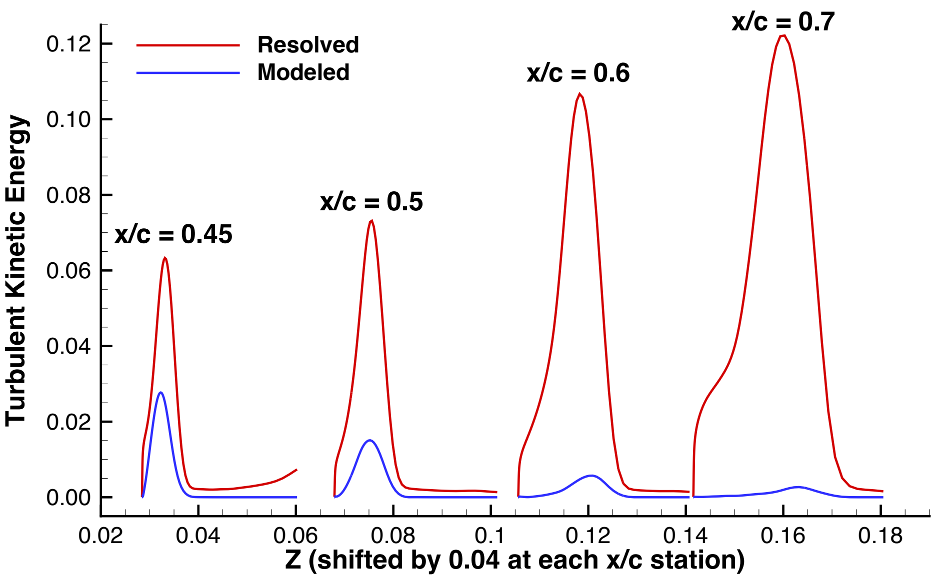


- Almost no difference in shielding function using DDES on UFG1 and UFG2
- RANS/NLES shielding function is set by the user based on steady or unsteady RANS precursor run, and does not change dynamically
- No indications from shielding function on why the solution is so sensitive to both grid resolution and model

Case 3a: Shock/BL Separation

Comparison of modeled and resolved turbulent kinetic energy (DDES)

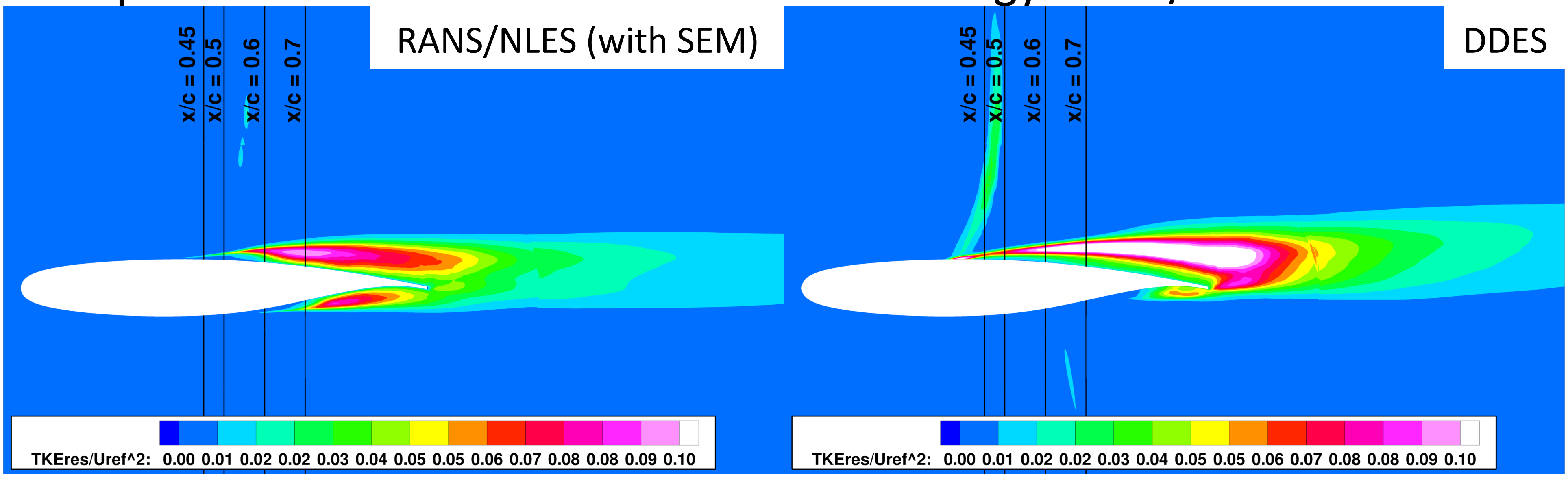


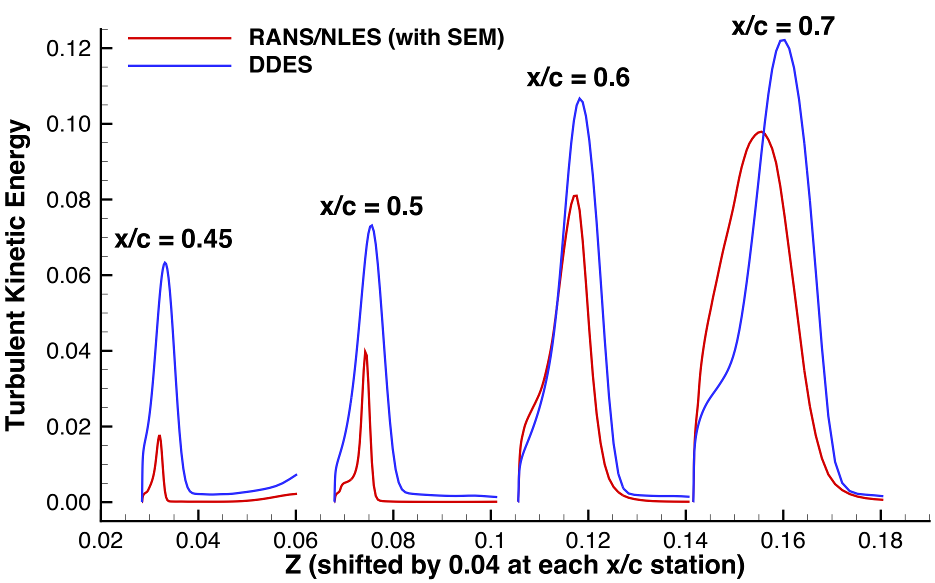


- Resolved TKE remains larger than modeled TKE downstream of shock
- Resolved TKE increases while modeled TKE decreases downstream
- Resolved TKE on the lower surface near the trailing edge is smaller than on UFG1.

Case 3a: Shock/BL Separation

Comparison of resolved turbulent kinetic energy RANS/NLES vs DDES





- RANS/NLES produces lower magnitudes of resolved TKE compared to DDES on the upper surface
- A much larger region of resolved TKE is observed on the lower surface using the RANS/NLES model
- Lack of resolved TKE on the lower surface using DDES may be changing the circulation around the wing

Summary

- A sequence of structured overset grid systems were generated for the BSCW from coarse to very-fine for RANS analysis and ultra-fine for Hybrid RANS/LES analysis
- Case 1a:
  - Discovered wing is not straight and that CAD must be used for grid generation
  - Good comparison to experimental Cp data achieved
- Case 1b:
  - Strong sensitivity to time-step was observed in drag and FRF
  - Less sensitivity to mesh resolution (may be due to high-order accurate spatial discretization)
  - Large discrepancies in FRF compared to experiment, but are consistent with reported results from other participants

Summary

- Case 3a (Ultra-Fine Grid 1):
  - Demonstrated accuracy improvement in surface pressure using DDES compared to RANS for shock/boundary layer separation.
  - Observed delay in transition to 3D turbulence at separation location related to reduction of resolved turbulent stresses caused by large eddy viscosity near the wall
- Case 3a (Ultra-Fine Grid 2):
  - Observed large sensitivity in shock location to mesh and hybrid RANS/LES model selection
  - DDES predicts shock to far upstream (may be caused by insufficient resolved TKE on lower surface near trailing edge)
  - RANS/NLES (with SEM) improves the accuracy of the shock location on both the upper and lower surface
  - Neither model does well of predicting Cp in the separated flow region

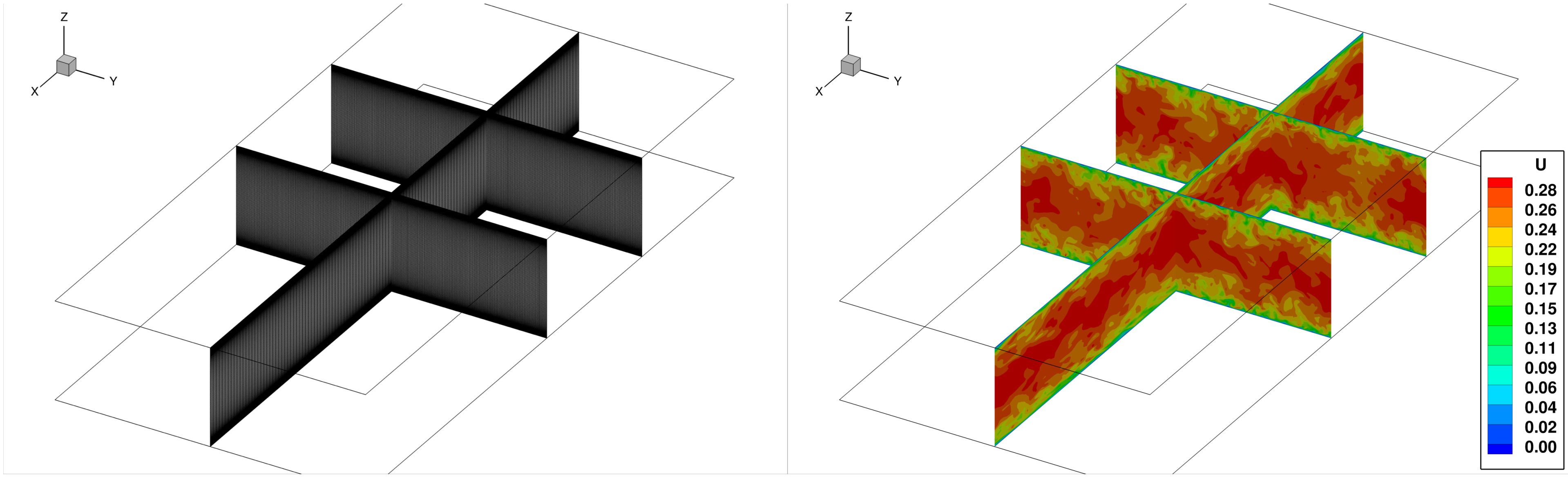
Future Work

- How appropriate is NLES as:
  - the mesh is refined
  - the artificial dissipation is reduced

- How appropriate is the RANS/NLES model in the interface

Fully Developed Channel Flow

Re_τ=395 $\Delta x^+ = 40$ $\Delta y_{wall}^+ = 0.75$ $\Delta y_{center}^+ = 10$ $\Delta z^+ = 10$

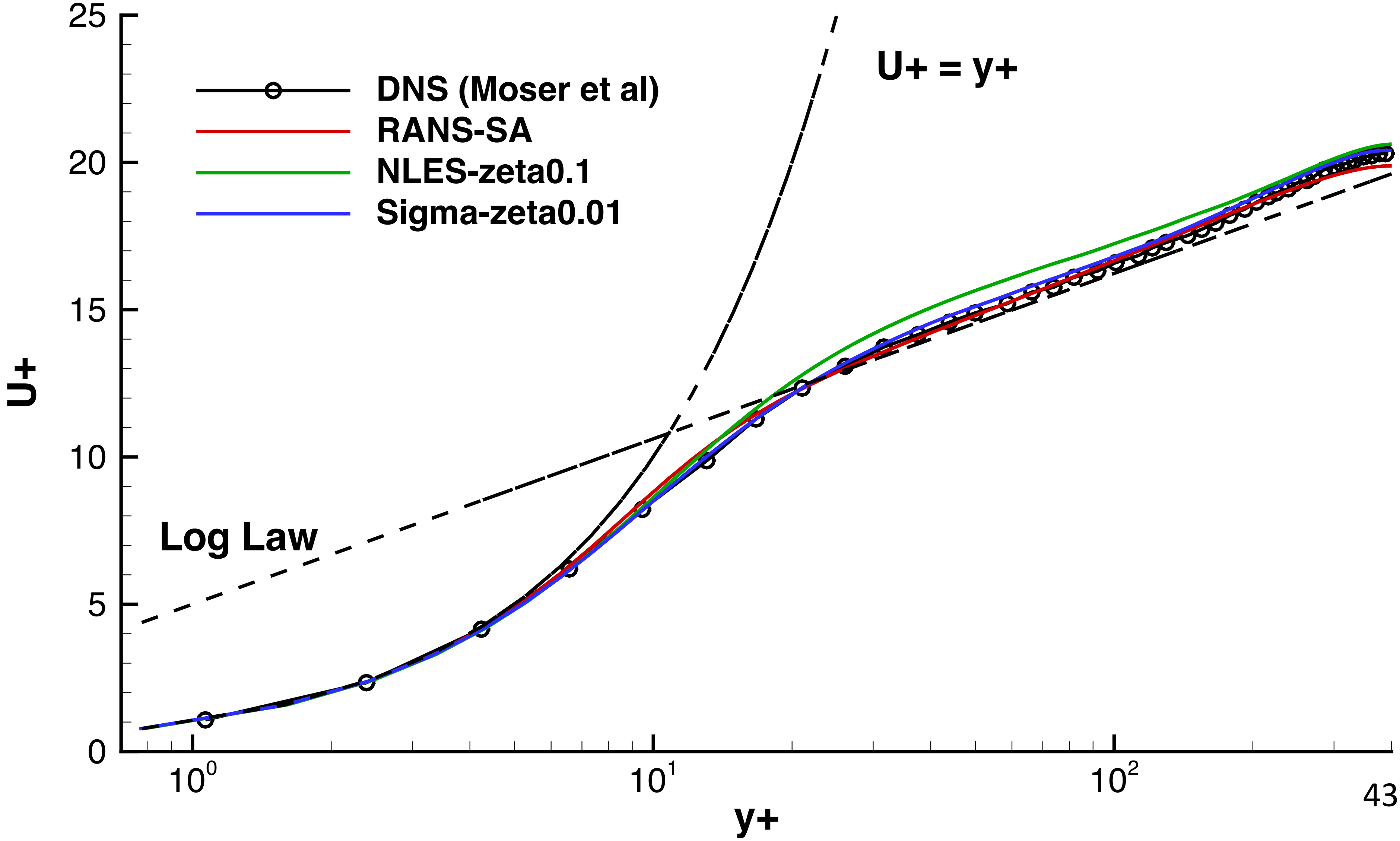


Objectives

- Demonstrate the accuracy of the LAVA solver for wall-resolved LES
- Determine the sensitivity of the NLES model to reduction of artificial dissipation
- Analyze alternative sub-grid scale models (such as the sigma model)
- Observe the solution behavior of the RANS/NLES model in the interface region

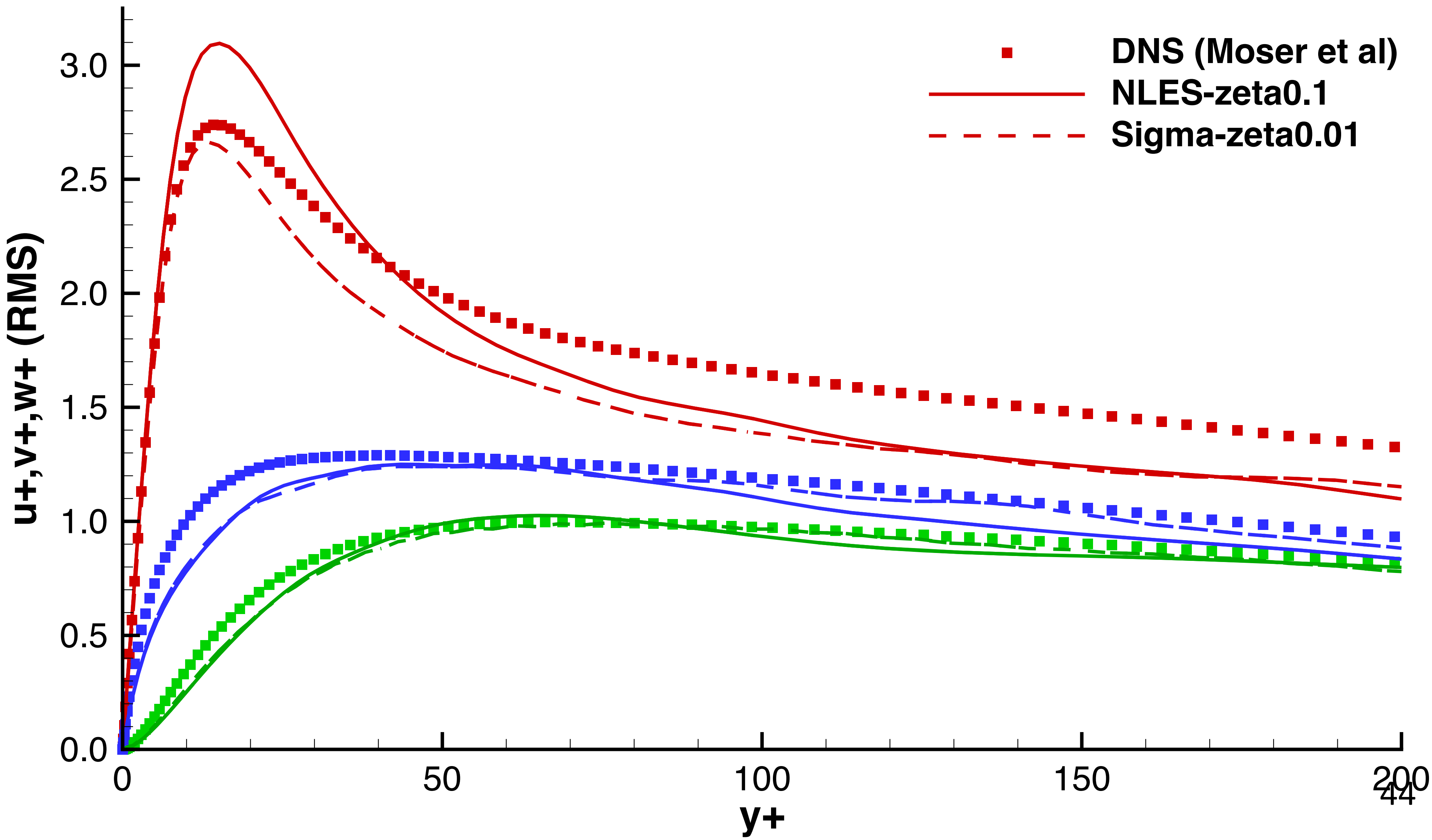
Fully Developed Channel Flow

Re_τ=395 Δt^+ = 0.5; Comparison of Boundary Layer Profile



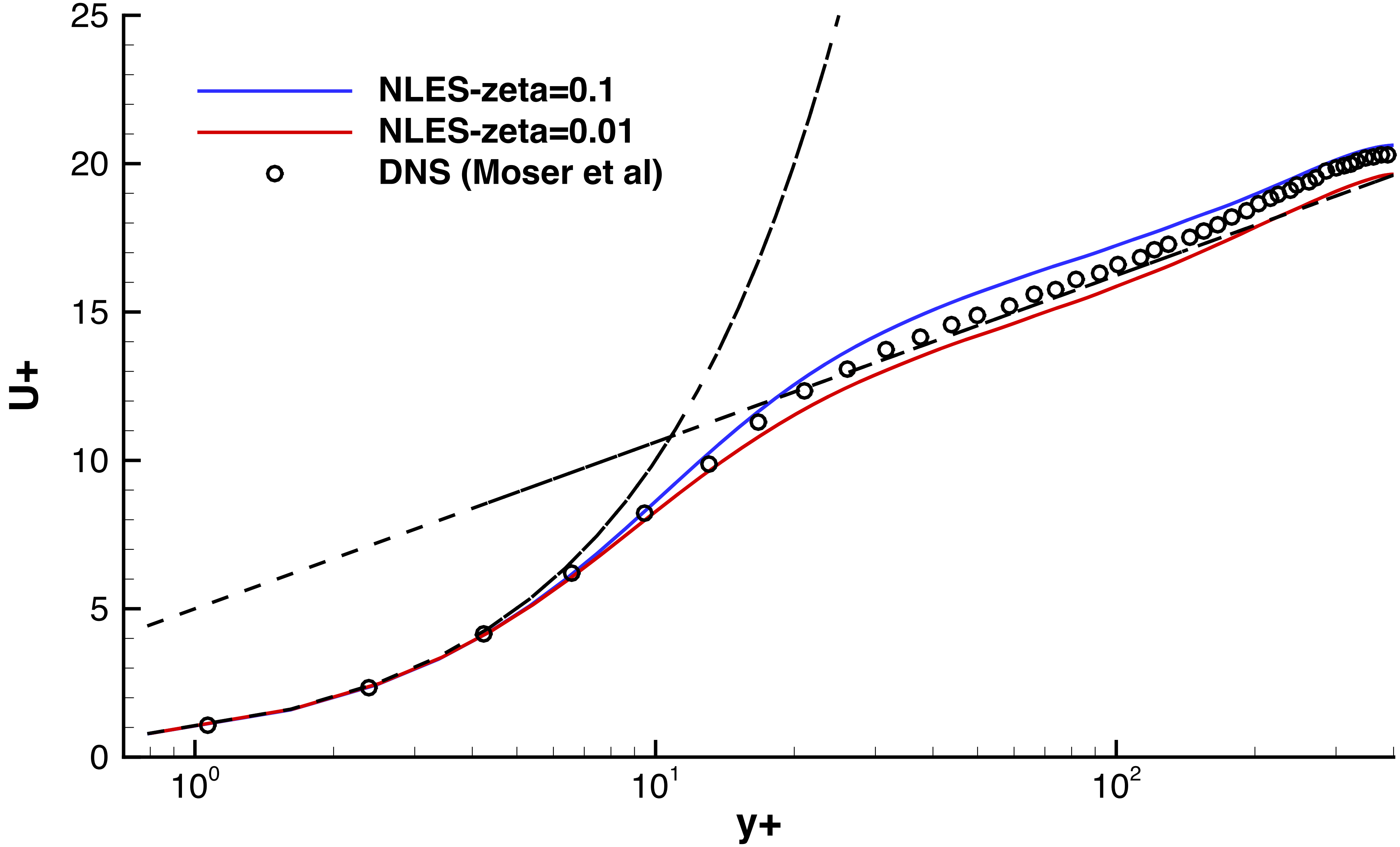
Fully Developed Channel Flow

Re_τ=395 Δt^+ = 0.5; Comparison of RMS



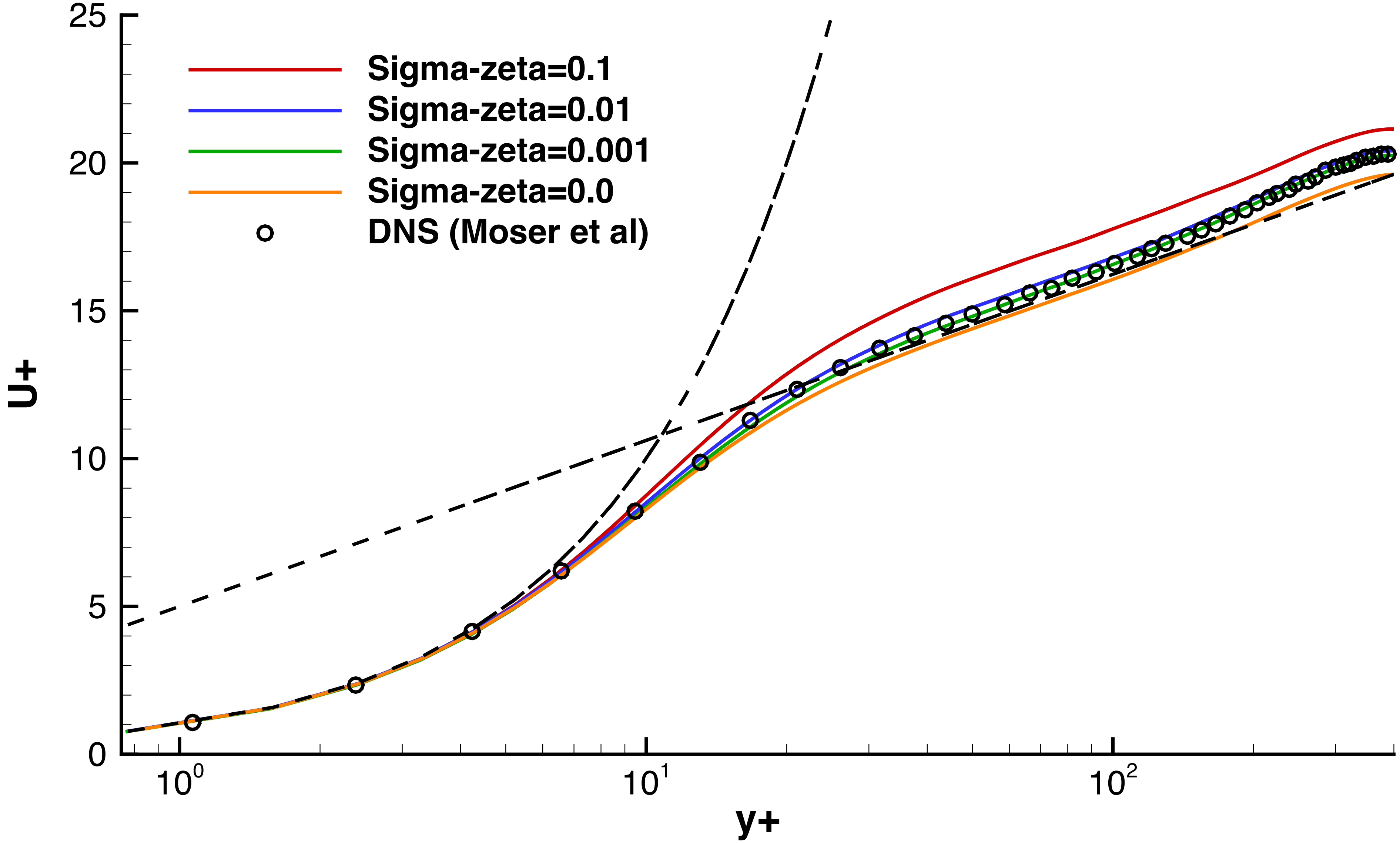
Fully Developed Channel Flow

Re_τ=395 Δt^+ = 0.5; NLES Sensitivity to Upwind/Central Blend



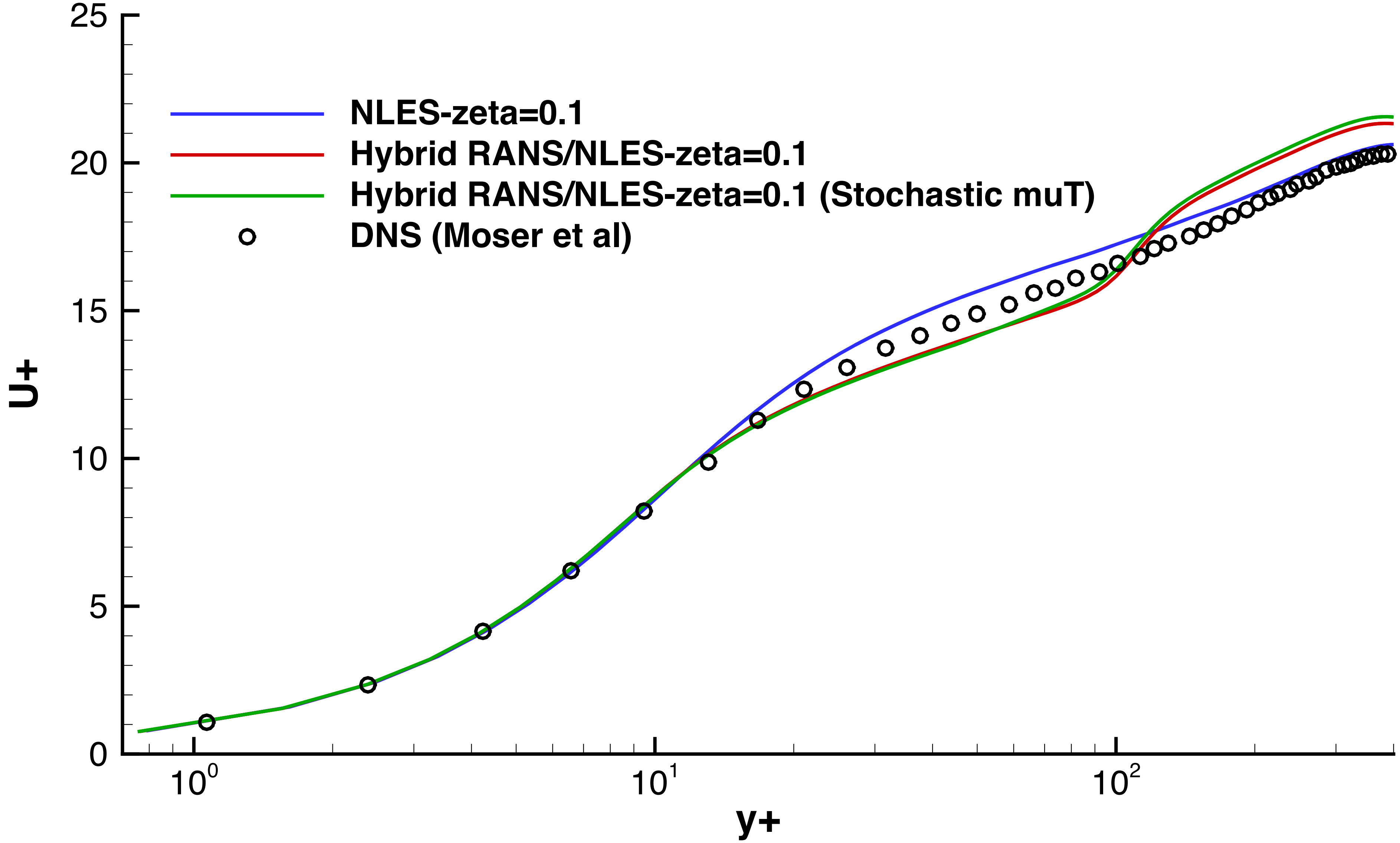
Fully Developed Channel Flow

Re_τ=395 Δt^+ = 0.5; Sigma Sensitivity to Upwind/Central Blend



Fully Developed Channel Flow

Re_τ=395 Δt^+ = 0.5; Failure of RANS/NLES in log-layer



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